D
1
3525
145

United States Department of Agriculture

Forest Service

North Central Forest Experiment Station

General Technical Report **NC-145**

Chunkwood: Production, Characterization, and Utilization

North Central Forest Experiment Station
Forest Service—U.S. Department of Agriculture
1992 Folwell Avenue
St. Paul, Minnesota 55108
Manuscript approved for publication June 6, 1991
1991

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.

FOREWORD

The concept of chunkwood was introduced in the mid-1970's by North Central Forest Experiment Station researchers. Chunkwood particles are much larger and more blocky than conventional, relatively flat, platy wood chips. This new technology of comminuting small trees into chunkwood was developed to provide an alternative bulk material that would enhance the utilization of trees for which there were limited existing markets. Although new possible uses for chunkwood have emerged, the original target markets for these particles were the wood energy and flakeboard industries.

After several years of chunkwood-related research conducted by the North Central Station's Forest Engineering Project in Houghton, Michigan, chunkwood evolved into a project of international interest and cooperation. In Paris in November 1984, an international program of cooperative research, entitled "Chunkwood - Technologies for Comminuting and Utilizing Forest Biomass as an Energy Source," was approved by the executive committee of the International Energy Agency (IEA). The IEA coordinates a program of research, development, and demonstration on all forms of biomass-for-energy. Countries participating in the chunkwood program were Denmark, Finland, Norway, Sweden, and the USA. From 1986 through 1988, researchers from all participating countries conducted research on various aspects of chunkwood.

Their research culminated in a conference jointly sponsored by the IEA chunkwood activity and another activity dealing with the drying and storage of wood fuels. The joint conference, "**Production, Storage and Utilization of Wood Fuels**," was held in Uppsala, Sweden, December 6-7, 1988. A two-volume set of proceedings, recommended for those interested in the international state-of-the-art on this subject, is available for 40 SEK (about $6) from:

Sveriges Lantbruksuniversitet
Institutionen for Skogsteknik
S-770 73 Garpenberg
Sweden

This General Technical Report is a collection of papers presented by North Central Forest Experiment Station researchers at the IEA conference in Sweden. Two additional papers are included that were not presented at this conference. These papers represent a compilation of the U.S. state-of-the-art on chunking machinery and chunkwood.

Contents

Page

Characterizing Chunkwood
Rodger A. Arola, Robert C. Radcliffe, and Joseph B. Sturos 1

Chunkwood Drying Research With Northern U.S. Hardwoods
Rodger A. Arola, Joseph B. Sturos, and Robert C. Radcliffe 16

Forest Roads Built With Chunkwood
Rodger A. Arola, Ralph J. Hodek, John K. Bowman, Gary B. Schulze 29

U.S. Chunkwood Machines
Rodger A. Arola, Joseph B. Sturos, and Robert C. Radcliffe 45

Airflow Resistance of Chunkwood
Joseph B. Sturos 60

Teardrop Chunker Performance
Joseph B. Sturos 69

Total-Tree Chunkwood as Raw Material for Flake Products
Bruce A. Haataja, Roy D. Adams, and Rodger A. Arola 78

Reducing Particle Dimensions of Chunkwood
Robert C. Radcliffe 88

Characterizing Chunkwood[1]

Rodger A. Arola, Robert C. Radcliffe, and Joseph B. Sturos[2]

Abstract.—Chunkwood has only recently been introduced as an alternative form of comminuted wood. Parallel to commercial use of chunkwood, whether it be in the energy or flakeboard industry, techniques and equipment to classify chunkwood must be developed. Conventional pulp chip classifiers are inadequate because of the differences in particle size between chunks and chips. Three distinctly different classifiers were tested for performance and to gain an understanding of how screens with round, square, or elongated openings discern between chunks having different particle geometry. Preliminary recommendations are made for a rotary laboratory classifier having interchangeable sets of screens with square, round, and elongated openings. Chunkwood particles may be too large for a particular application, and conventional pulp-size chips may be too small. Through the use of three experimental techniques, it was demonstrated that chunkwood can be reduced into a more homogeneous mix of intermediate-size particles that could enhance utilization. The results from the chunkwood reduction trials are presented. The bulk density of chunkwood produced from several North American tree species ranged from 20 to 24 pounds per cubic foot. Natural angle of repose for red maple was about 43 degrees.

INTRODUCTION

The concept of chunking and chunkwood is relatively new. This international conference demonstrates that chunkwood is now being recognized as an alternative raw material form for such uses as energy, flakeboard, and even low-volume forest road building.

Chunkwood particles are generally much larger and longer in the fiber direction than conventional pulp chips. They can range in size from that of an individual cigarette up to entire discs equal to the diameter of the tree or log at the point of cut (fig. 1). Chunkwood particles may be distributed over a wide spectrum of sizes or concentrated in a narrow size range. What ultimately determines the particle sizes is the chunker design and operating characteristics as well as species, size, and character of the material being chunked.

As industry begins to use chunkwood in various ways, commercial and laboratory techniques and equipment to classify chunkwood by size will be needed. Extensive work has been done to develop equipment and techniques to classify wood chips. Fuller (1985) presents a comprehensive overview on the general subject of classification methods now in common use and provides more than 70 literature references on the subject. However, conventional wood chip screens are generally too small to classify chunkwood.

In the laboratory, researchers need to define the size distribution of chunkwood to help explain

[1]*Paper presented at the International Energy Agency/ Bioenergy Conference, Task III/Activity 6 and 7 "Production, storage, and utilization of wood fuels." [The Swedish University of Agricultural Sciences, Uppsala, Sweden, December 6-7, 1988.]*

[2]*Rodger A. Arola, Robert C. Radcliffe, and Joseph B. Sturos are Research Mechanical Engineer, Electronic Technician, and Mechanical Engineering Technician, respectively, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

Figure 1.—*Comparison between chunks and chips.*

research results where particulate size or gradation influences results. An international laboratory screening standard is needed for chunkwood. Commercial utilization of chunkwood will be accompanied by a need to screen the material to sort acceptable from unacceptable fractions or to determine if the bulk quantity meets particulate specifications for the intended application. For example, at an energy plant, the proportionate distribution of particles by size may be used as the criterion to determine if established fuel specifications for a particular combustor are met.

In those situations where some of the chunkwood particles are too large for use, the oversized particles can be reduced by mechanical means. Regardless of how chunkwood is used, it is a bulk material and must be handled accordingly. It has unique characteristics in relation to standard pulp-size chips or hogged fuel.

One objective is to present research findings from using several experimental approaches to classify chunkwood according to size. A second objective is to present research results from using several mechanical approaches to produce a more homogeneous mix of particles intermediate in size between chunkwood and conventional pulp chips. The term "reduced chunks" will be used in this paper when referring to these intermediate-size particles. A third objective is to present basic data important to materials handling: angle of repose and bulk density. This paper is organized into three sections that discuss these objectives.

CHUNKWOOD CLASSIFICATION

Equipment and Methods

Four screening devices were tested to classify chunkwood by size (fig. 2). Two of the devices, a Williams Standard Pulp Testing Apparatus[3] and a Sweco Vibro-Energy Separator (24-inch-diameter model), were modified commercial classifiers.

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others that may be suitable.*

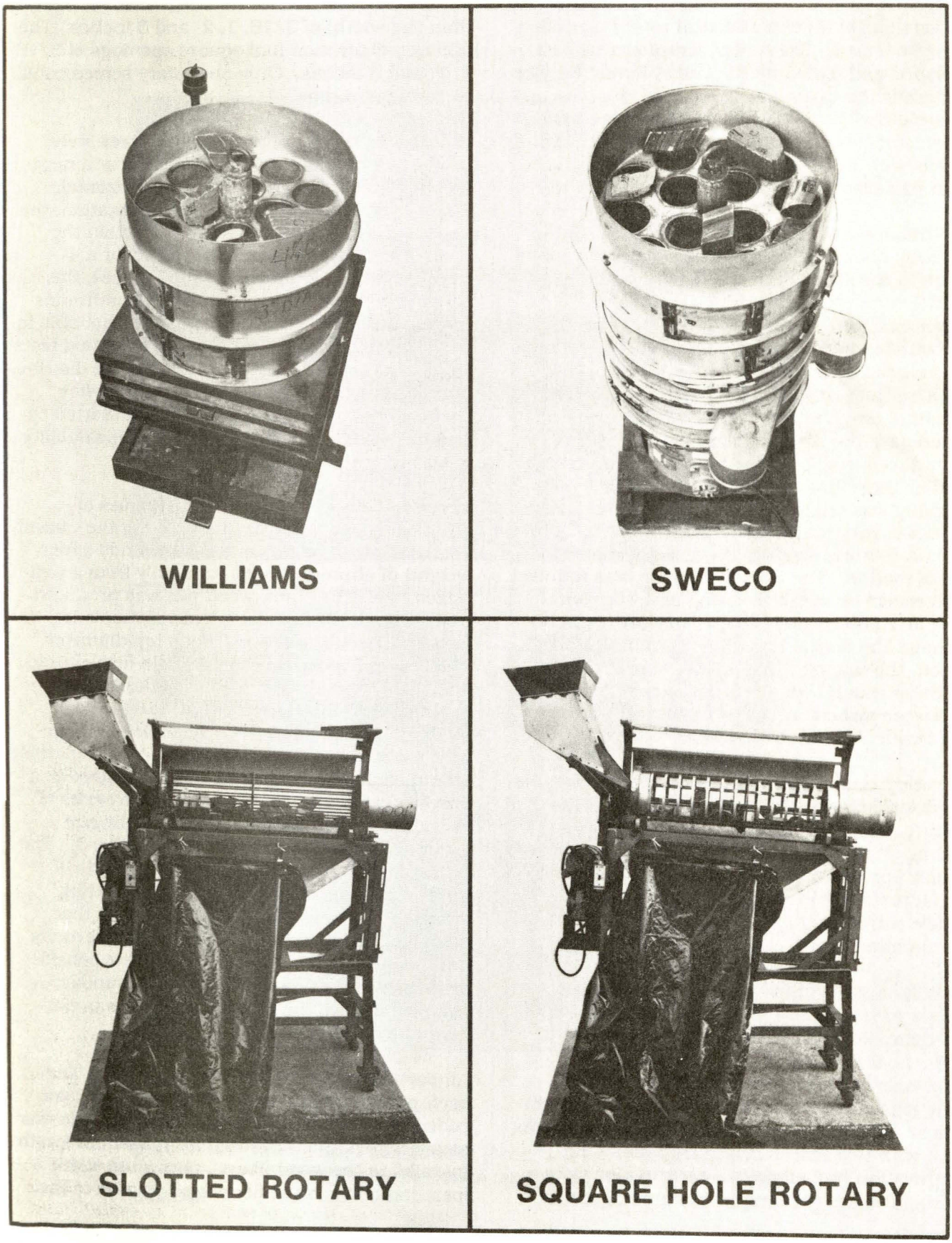


Figure 2.—*Four types of classifiers tested.*

Two versions of an experimental rotary classifier were also tested. The rotary classifier was first developed and tested by the USDA Forest Service to upgrade the quality of whole-tree chips by removing bark, grit, and foliage (Sturos 1973). All screening devices were modified by fabricating screens with larger openings consistent with the larger particles typically found in chunkwood.

The Williams and Sweco classifiers both used a vibrating stack of screens; each successive lower screen in the stack had smaller, round holes. The Williams classifier shook at a lower frequency and more vigorously than the Sweco. The translational shaking motion of the Williams was induced by a crank arm rotating at 171 cycles/minute in a fixed 2-1/8-inch-diameter horizontal circular path. This planar orbital motion gave the screen 2 degrees of freedom. The induced motion of the Sweco was much more complex than that of the Williams. The screen assembly was suspended on springs that enabled pitch, roll, rotation, and vertical components in addition to horizontal—thus, 6 degrees of freedom of motion. The Sweco's motion was induced by an eccentric weight rotating in a horizontal plane at 1,200 revolutions per minute (rpm). Although the Sweco had more possibilities for motion, the magnitude of actual screen movement was much less than that of the Williams. The Sweco system appeared to vibrate at a very high frequency with little visible movement.

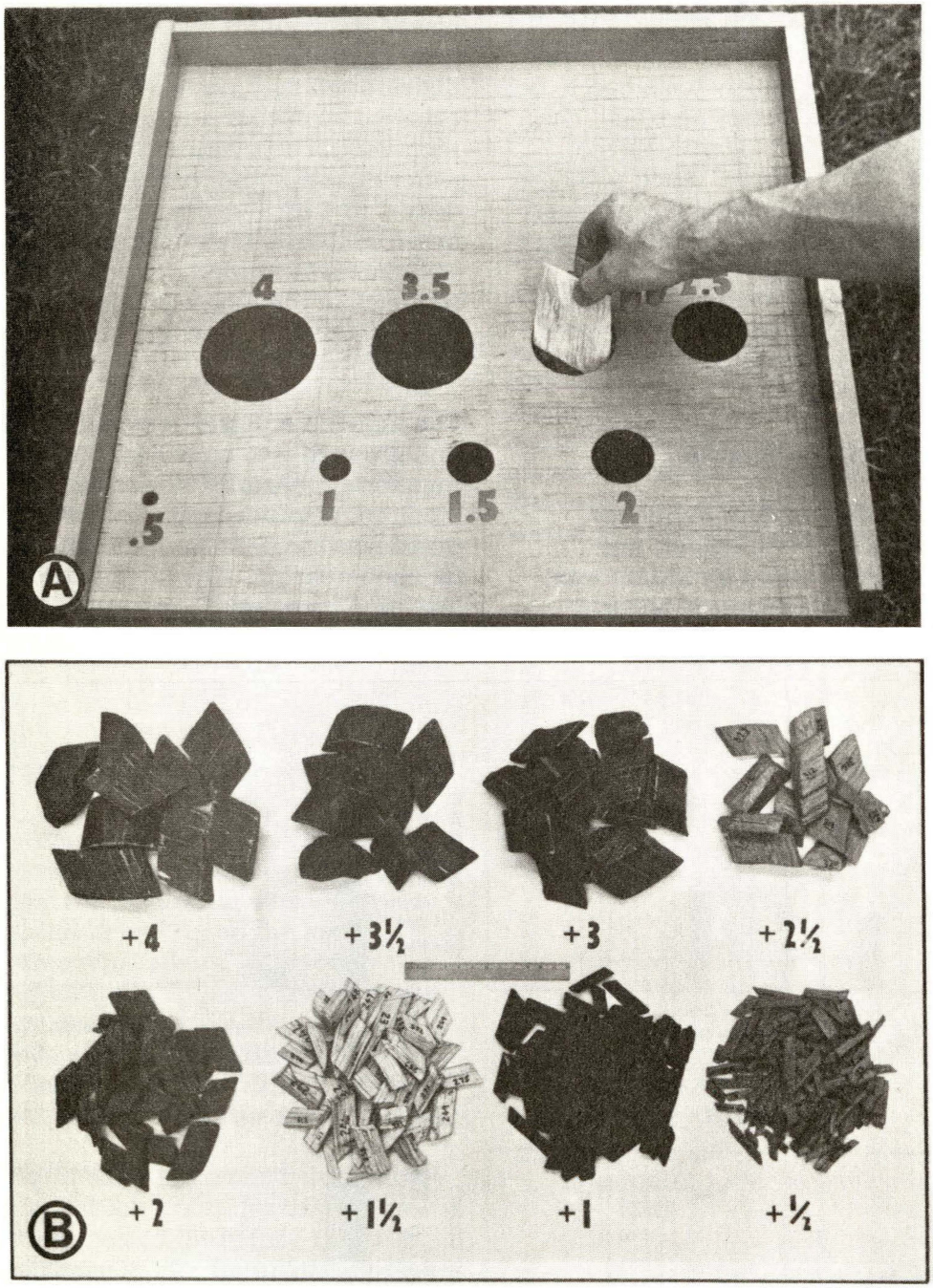
The rotary classifier had a set of interchangeable cylindrical screens that were rotated at a speed of 77 surface feet per minute (79 to 127 rpm depending on the particular screen diameter in use) about a horizontal or slightly negative inclined axis (adjustable). The rotary screen imparted a particle tumbling action within the circular screen chamber.

The Williams classifier was tested with five screens having 3/16-, 1-1/8-, 2-, 3-, and 4-1/4-inch-diameter round holes. The Sweco had 3/16-, 1-, 2-, 3-, and 4-1/4-inch-diameter round-hole screens. Both the Williams and Sweco classifiers were tested with all screens in place at the same time. The rotary classifier was tested with two screen configurations. One configuration had elongated rectangular slots (openings where the length was much greater than the width) of 3/16, 1, 2, and 3 inches. The other configuration had square openings of 3/16, 1, 2, and 3 inches. Only one rotary screen could be tested at a time.

Both configurations of the rotary screen were tested in a horizontal orientation and at a negative 5-degree inclination from the horizontal. When operated in the horizontal orientation, the ends of the screen were plugged to retain the particles within the screen chamber for a 4-minute test. When inclined at 5 degrees, the screen ends were left open to allow continuous feeding and discharge of the particles not able to pass through the screen. The classification tests were used not only to determine the size distribution of particles, but also to determine what particle characteristics each classifier sorted by and to establish some indication of repeatability of sort for each classifier.

Three so-called "standard" test samples of chunkwood were prepared for testing the classifiers. Each sample contained 30 pounds (green weight) of chunks chosen randomly from a well-mixed pile. The chunkwood pile was produced from a single 40-foot debarked red maple log having a 7-inch butt and 3-inch top diameter. The Forest Service prototype single-disc chunker was used to produce the chunks (Arola 1984, Arola *et al.* 1985, Barwise *et al.* 1984). Each standard sample was first oven dried to 0-percent moisture content (MC). Every single particle within each standard sample was assigned to a size group. A piece of plywood with a series of round holes was used to determine the size group assignments for each particle (fig. 3). The holes ranged in diameter from 1/2 inch to 4 inches in 1/2-inch increments. The sorting criteria were based on the smallest hole that each particle would pass through. All particles passing a 1/2-inch-diameter hole were considered fines and discarded from each standard sample because the quantity of fines was not germane to the testing.

All particles were individually numbered, and each particle within each size group was color coded for easy identification. Every particle was also weighed and measured for maximum length (parallel to the wood fibers), maximum width (perpendicular to the fibers and parallel to the



igure 3.—*A. Device used to establish three "standard" chunkwood sample sets for classifier performance testing. B. Typical "standard" sample.*

major fracture planes visible on the chunk ends), and maximum height (perpendicular to both the wood fiber and the major fracture planes).

The tests were not randomized because of the number of screening options and because some screens used in the slotted rotary tests had to be converted into square-hole rotary screens. The sequence of testing was the Williams, Sweco, rotary slotted, and rotary square. Each standard sample was individually run through each classifier type. The samples were split as necessary so as not to overload the screen. The serialized particles retained on each screen were recorded by number. Three replications were made with each standard sample set to determine the repeatability of each classifier.

Classification Results

All three sample sets had similar frequency distributions for length, width, height, and weight (fig. 4). The distribution for length was bell-shaped with 40 to 50 percent of particles falling into the 2- to 3-inch range. Most remaining particles were in the 1- to 2-inch and the 3- to 4-inch-length classes. All particles were less than 6 inches long. The distribution for particle height was heavily skewed to the smallest height class—between 80 and 90 percent of the particles were in the 0- to 1-inch class. The particle width distribution was also skewed to the smaller width classes. About 50 percent were in the 0- to 1-inch-width class with progressively fewer in the wider classes. About 80 percent of the particles were 1 to 4 inches long, 1/2 to 2 inches wide, and less than 1 inch high, and weighed less than 100 grams (oven-dry). However, there were particles in the larger length, width, and height classes, some quite large, weighing up to 600 grams (oven-dry).

The individual particles were ranked by weight and grouped into quartiles. The quartile groupings were arbitrarily labeled as small, small-medium, medium-large, and large particles. Also noted was the percent of the total sample weight for each quartile. The large particle quartile grouping made up 82 percent of the total weight.

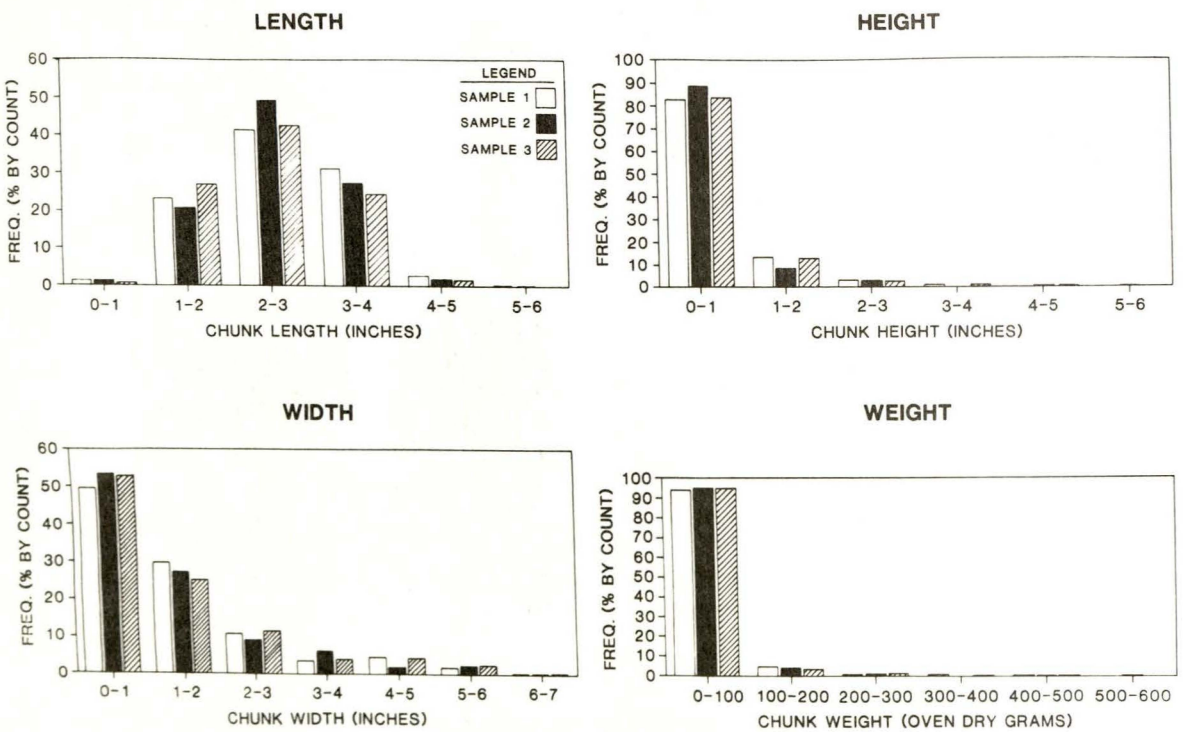


Figure 4.—*Distribution of particle length, height, width, and weight for each of three standard sample sets.*

Percent total by count	Particle size	Percent total by weight
25	Small	2
25	Small-medium	4
25	Medium-large	12
25	Large	82

Each standard sample was classified three times with each screening device to determine repeatability. Repeatability was based on the percentage of particles retained on the same screen three out of three times.

Screen type	Particle retention[1]	
	Percent by count	Percent by weight
Rotary slotted screen @ 0 degrees	92	92
Rotary slotted screen @ 5 degrees	93	81
Rotary square screen @ 0 degrees	92	82
Williams	89	86
Rotary square screen @ 5 degrees	79	80
Sweco	78	68

[1]Represents mean results of three standard test samples.

The most repeatable classifier tested was the rotary slotted screen inclined at a negative 5-degree angle from the horizontal where 93 percent of the particles ended up on the same screen for all three replications. The rotary screen in the horizontal position, whether it had slotted or square openings, gave the next best repeatability, followed by the Williams. The Sweco was the least repeatable with 78 percent by particle count ending up on the same screen.

There was no significant difference between the screen results by particle count for any of the screening machines tested (Student t-test at a 95-percent confidence level). By weight, however, there was a significant difference between the Sweco and the horizontally positioned rotary slotted screen at the 95-percent confidence level. In a practical sense, the rotary slotted classifier was the most repeatable. The rotary square and the Williams classifiers were very similar and gave acceptable performance. The Sweco gave the poorest performance.

To gain some insight into how round, square, and elongated screen openings see the particles to make size sortments, linear correlation coefficients were calculated (using Pearson product moment correlation method) between screen type and size and various idealized particle measurements. Several hundred data points were used to calculate these coefficients. The minimum-edge, mid-edge, and short-diagonal gave the best correlation (fig. 5). The two round-hole screens (Williams and Sweco) and the rotary square-hole screen in both inclinations had the highest correlation with the short-diagonal dimension. The rotary screen with elongated slot openings sorted by the minimum-edge dimension.

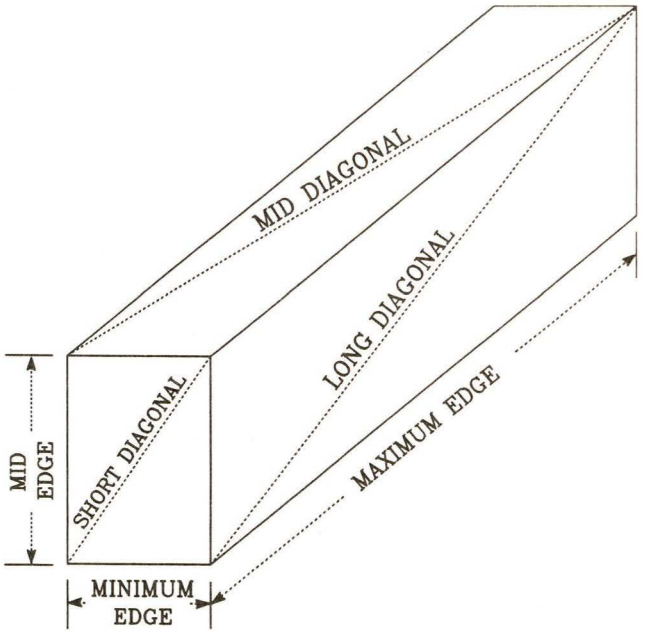


Figure 5.—*Principal measurements made on an idealized particle.*

Screen type	Minimum-edge	Mid-edge	Short-diagonal
Williams	0.81	0.92	0.94
Sweco	.78	.89	.91
Rotary slotted @ 0 degrees	.87	.62	.71
Rotary slotted @ 5 degrees	.88	.64	.73
Rotary square @ 0 degrees	.81	.92	.94
Rotary square @ 5 degrees	.80	.91	.92

The particle behavior in each of the three classifiers was unique. With the Williams machine, the particles slid and bounced over the surface of the top screen. With the Sweco machine, the high frequency of vibration and small amplitude of motion merely caused the particles to gently "buzz" around on the screens. In contrast, the violent particle tumbling action in the rotary classifier gave the particles the most exposure to the screen.

These important characteristics should be considered when creating particle sortments. For example, the sorting goals would likely be different when classifying energy wood to determine if it met established fuel specifications for a particular combustor as opposed to sorting particles for feedstock to a ring flaker as used in the structural flakeboard industry. A round-hole screen would probably be the best choice for fuel classification, whereas a rotary slotted screen would likely be a good choice for prescreening particles as input to a ring flaking machine.

CHUNKWOOD REDUCTION

Three mechanical devices were used to produce particles of a size intermediate to pulp chips and chunkwood (fig. 6). Two devices, a hammermill and a spiked roll assembly, were used after chunking to further reduce the size of chunkwood particles. The third device was a roll crusher that severely crushed the test logs before chunking.

Equipment and Methods

The hammermilling device was a small commercial machine. A hopper fed material to the chamber housing three pivoted weighted bars mounted on a shaft rotating at 1,750 rpm. As the shaft rotated, the weighted bars impacted the material entering the shrouded chamber. To prevent excessive reduction of the chunkwood, the bottom grate was removed to minimize retention time within the reduction chamber.

The spikes in the spiked roll assembly were used to penetrate the chunks to cause fracturing along the grain. This was an experimental machine designed by mechanical engineering students at Michigan Technological University under the guidance of a Forest Service engineer. The machine's principal feature was two opposing rolls with 3-inch-long spikes attached. The spikes were made from hardened 3/4-inch-diameter hex head bolts with the threaded end sharpened to a 60-degree cone. The bolts were welded to the rolls on a 2- by 3-inch grid and inclined at a 60-degree angle from a tangent to the roll surface towards the direction of rotation. This configuration provided easier spike penetration of the chunkwood particles and more aggressive feed. As the rolls rotated, the spikes intermeshed to varying degrees depending on the nip spacing between the rolls. The power source was a hydraulic motor connected to a 50-horsepower hydraulic supply. (An industrial version of this machine is envisioned as having successive stages of opposing roll pairs with progressively closer nip spacing. In such a unit, the chunks would be reduced to smaller and smaller particles as they pass through each succeeding stage.)

The machine used to crush the test logs before chunking was an experimental unit built by the Forest Engineering Research Institute of Canada (FERIC) (Barnett *et al.* 1986). It featured two sets

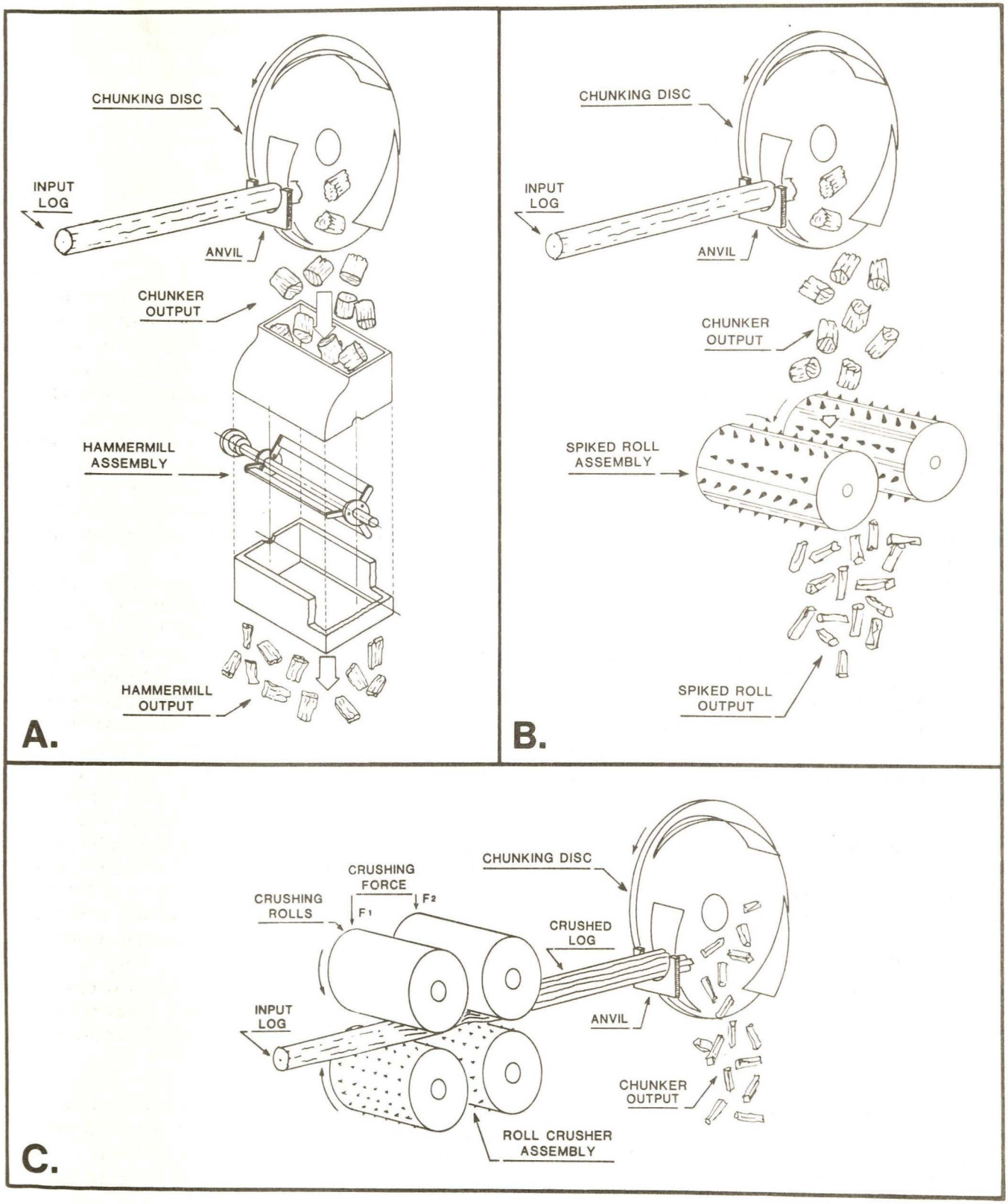


Figure 6.—*Three experimental reduction methods used to obtain intermediate-sized particles.*

of opposing 18-inch-diameter rollers that were fitted with detachable ribbed sleeves for positive feeding. Hydraulic cylinders exerted a crushing force on each upper roller. With the log (or tree) positioned between the first set of rollers and with the rotational drive engaged, the workpiece was drawn into the roller mechanism where it was crushed by the first roll set and crushed further by the second set. The severity of crushing was controlled by varying the hydraulic pressure and rotational speed of the rollers. The crushed logs were then chunked.

Testing Program

Red maple (*Acer rubrum*) and aspen (*Populus tremuloides*) were chosen as the test species. Green, 8-foot logs, under 8 inches in diameter of both species were obtained from a local timberstand. The logs were chunked with the Forest Service experimental single-disc chunker (Barwise *et al.* 1984). The chunks from each log were collected separately and bagged.

Hammermill

Before hammermilling the chunks, they were first classified using the rotary screen with square holes. These results served as a treatment control. The hole sizes were 0.2, 1, 2, and 3 inches. The screen was operated at a rotational speed of 100 rpm and inclined at 5 degrees from the horizontal. The chunks were then processed through the hammermill. After one pass through the mill, the reduced particles were collected and reclassified on the rotary screens. The particle size distribution of the hammermilled material was then compared against a control to determine how effectively the hammermill reduced the chunks into a more homogeneous mix.

Spiked Roll

The chunks were first classified with the rotary square-hole screen as above to establish the treatment control size distribution of particles. The material was then inputted to the spiked roll assembly with the points of the spikes spaced 1/2 inch tip to tip. The output was re-classified. The output from the first stage reduction was then used as the input for a second stage reduction with the spike tips intermeshing by 1/2 inch. The second stage output was classified before using it as the input to the third stage reduction with the spikes intermeshing by 2-1/2 inches. The particle size distribution after each of three stages was compared to the initial distribution. An alternative future approach could take only the larger particles as input to the second and third stages. A cascading system of rolls would be envisioned.

Roll Crusher

Five aspen and five red maple logs, 8 feet long, were chunked, and the particles were classified. This material was the control sample that chunks produced from the pre-crushed logs would be compared to. A similar quantity of randomly selected logs of each species was roll-crushed and then chunked. A representative quantity of particles from each crushed and chunked log was collected and classified. The size distribution of particles from chunking crushed logs was compared to the control chunks from uncrushed logs.

Reduction Results

There were no statistical differences in the size distribution of particles between aspen and red maple. For this reason, the data for the two species within a treatment were averaged for presentation of results.

The distribution of chunks produced from solid logs is skewed to the larger particle sizes (fig. 7). The distribution of particles that resulted from all three experimental treatments had an approximately normal distribution. Clearly, all three reduction techniques were successful in producing a more homogeneous mix of smaller particles.

Because of the severity of hammermilling, this treatment produced the greatest amount of fines—almost double that of the other two treatments. For the same reason, there was a greater change in the distribution of particle sizes from the hammermill. The greatest change resulted from three passes through the spiked roll assembly at progressively closer nip spacings. Chunking crushed logs resulted in the most even distribution of particle sizes.

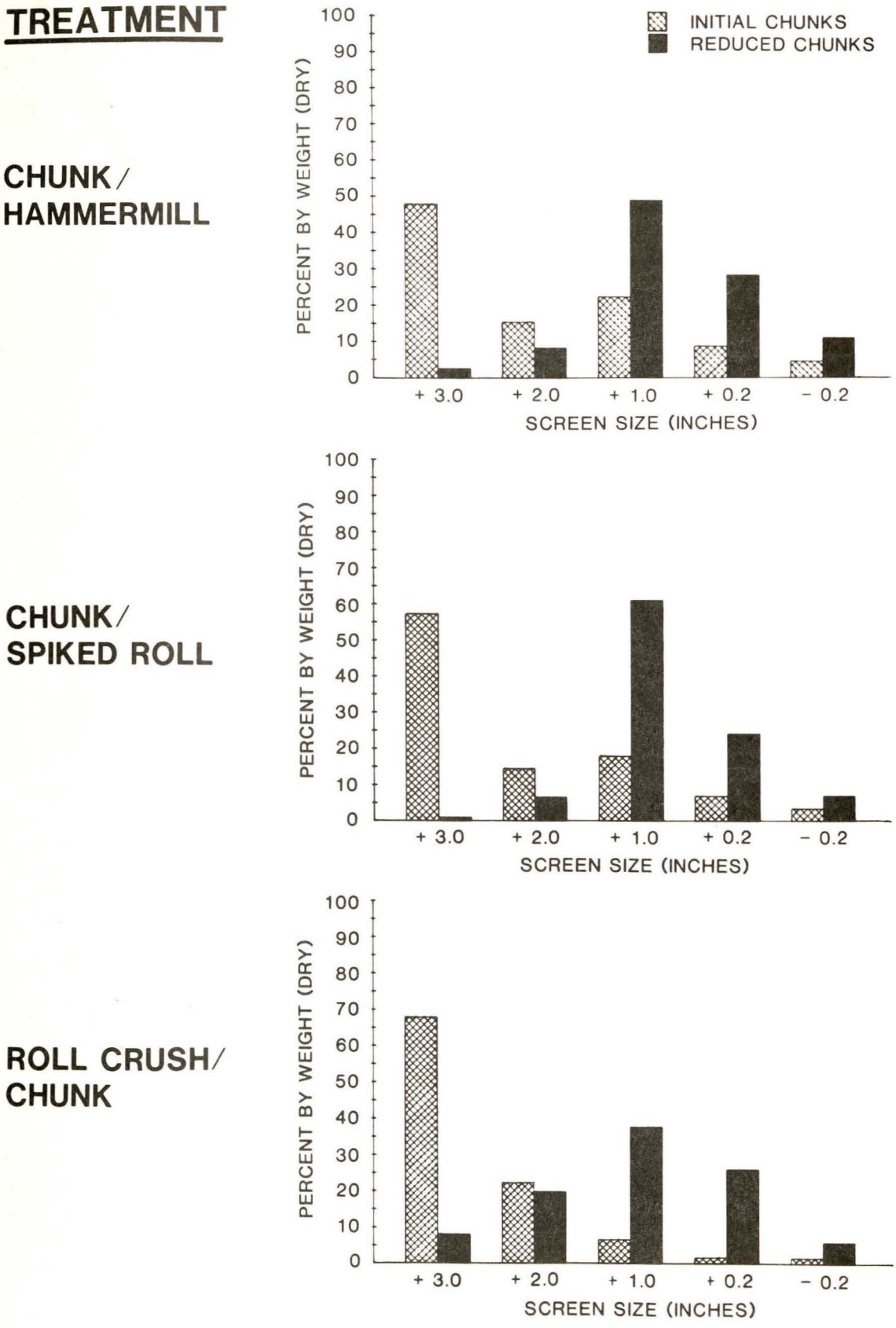


Figure 7.—*Mean before-and-after particle size distribution for the three experimental reduction methods used.*

The hammermill was fast, relatively trouble free, simple, and had low energy requirements—the 3-horsepower electric motor was sufficient. The three-pass system through spiked rolls is more complex mechanically and more energy intensive. Even with a 50-horsepower hydraulic power supply, the machine stalled on some larger chunks—particularly those with knots. The spiked roll assembly was outfitted with cleaning fingers to prevent particles from accumulating between the spikes. Although the roll crushing pre-treatment was simple and produced relatively good results, its principal disadvantage was in handling the crushed logs before chunking. If this approach were used, the crushed logs (trees) emerging from the crusher should be immediately funneled to the chunker's feed rolls. Another alternative is to compress the crushed stems into bundles before chunking to facilitate feeding and to increase chunking productivity.

With each successive pass of the entire sample through the spiked roll assembly, there was a progressive reduction in the amount of particles in the larger size classes and a continuous increase in particles in the 1-inch screen class (fig. 8A).

The distribution of particles resulting from each reduction technique was significantly different from the original chunkwood distribution (fig. 8B). Also, the particles from chunking pre-crushed logs had a different character from those produced by the other two treatments. The roll crushed logs were "flimsy" and hard to handle. Because of this, the cutting blades on the chunker were not always effective in severing particles of a uniform length—there were more long, stringy pieces.

It was assumed in this work that the rotary slotted classifier used did not produce any significant change in particle sizes. Even though there was a particle tumbling action, the impact on particle reduction was minor in comparison to the extreme severity of the reduction machines used. No attempt was made to measure the reduced particles outputted from the three chunkwood reduction approaches to describe their geometry.

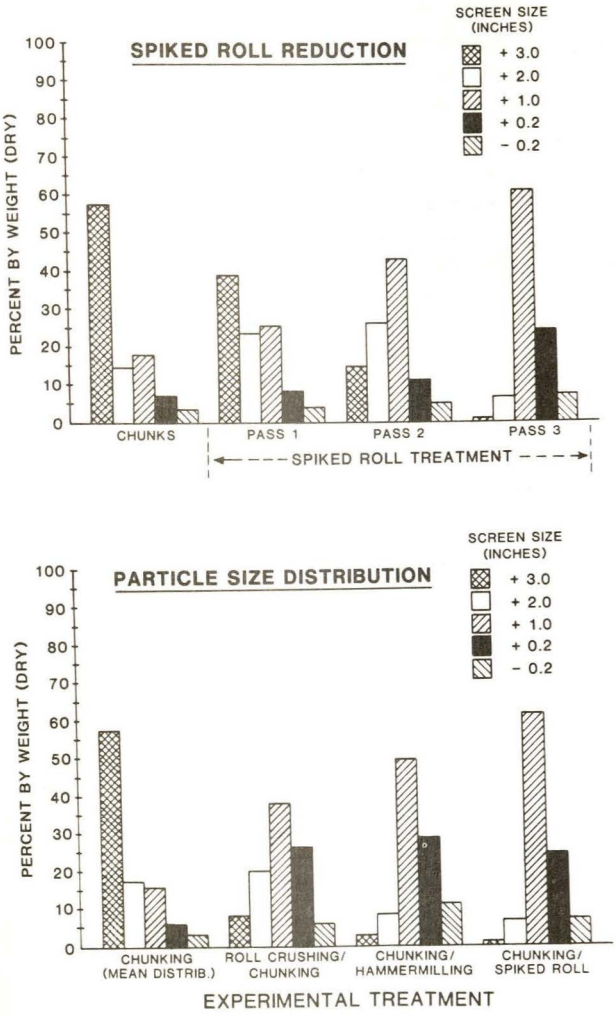


Figure 8.—*Particle size distribution: A. After successive passes through the spiked roll assembly; B. By experimental treatment.*

OTHER CHARACTERISTICS

Experiments were conducted to determine angle of repose and bulk density, two important characteristics of any material handled in bulk form.

A simple experiment was conducted to determine the natural angle of repose of chunkwood. The Forest Service prototype chunker was used to produce a large quantity of chunkwood from freshly-cut, whole red maple trees. The chunks were trickled onto an inclined conveyor raised to

a height of 12 feet. As the chunk pile grew in height, photographs were taken from a fixed location 90 degrees from the conveyor line. The angle of repose was then scaled from the photos. Measurements were periodically taken at pile heights between 4-1/2 and 9 feet. At the final 9-foot conical pile height, photographs were taken at 90-degree increments around the pile. The mean value of these four measurements was taken to be indicative of the angle of repose. The mean value was 43 degrees. By the time the pile reached a height of 6 feet, the natural angle of repose was established.

The bulk density of chunkwood was obtained by filling a box of known volume and then weighing the filled box. The weight of chunks was determined by deducting the tare weight of the box. The bulk density of several common Lake States species nominally ranged between 20 and 24 pounds per cubic foot with a nominal mean value of 22.

Species	Test bolt		Chunkwood
	Specific gravity	Moisture content	Bulk density
		Percent	*Pounds /cubic foot*
Populus 'Tristis'	0.30	47	-
Balsam fir	.36	57	21.8
Aspen	.39	50	19.5
Jack pine	.39	52	22.8
Red maple	.51	40	22.6
White birch	.53	45	22.1
Sugar maple	.58	38	24.4
Mean value			22.2

CONCLUSIONS

The Williams classifier and the rotary classifier with either square holes or elongated slots did a satisfactory job of classifying chunkwood by size and gave good repeatability.

The performance of any classifier is directly related to the extent of particle motion it induces. This is especially true for chunkwood. Its blocky, angular character makes the particles prone to lodge in an opening if bouncing and particle movement do not prevent this.

The rotary classifier, by its operating characteristic, induced the best particle motion because of the tumbling action within the screen chamber. The Williams classifier induced good particle motion because of the amplitude of planar motion of the screens. Because the Sweco induced essentially no jumping or bouncing of the particles on the screen decks, this classifier performed poorly.

The classification results obtained with the different classifiers tested were correlated against measured and calculated dimensions of an idealized particle. Screens having circular or square holes sort particles by a different criterion than screens with slots or elongated openings. As a general statement, square- or round-hole screens have the highest correlation with the short-diagonal of the particle. Screens with elongated slot openings sort by the minimum-edge dimension (in other words, they classify more by thickness). The sorting objective will influence the selection of geometry of screen openings.

If chunkwood particles are too large for a given application, they can be readily reduced to a more homogeneous mix of smaller particles. As post-chunking treatments, both hammermilling and penetration by spiked rolls were effective in reducing the size of chunks. Severe crushing of logs (or trees) was also an effective pre-chunking treatment to obtain particles intermediate in size between normal chunks and chips. The authors feel that hammermilling is the simplest, quickest, most reliable, and least energy intensive of the approaches tried.

RECOMMENDATIONS

Classification

The commercial Williams chip classifier, when modified by replacing some of the standard chip screens with screens having much larger holes, does an adequate job of classifying chunkwood and gives good repeatability. The modified Williams classifier could be used as a laboratory screen to obtain the size distribution of particles when it is not important to distinguish between elongated or flat particles from blocky particles. For example, the Williams classifier could be

recommended for use in determining the size distribution of chunkwood as a fuel.

Based on the experimental results and authors' opinions gained by observing the classification devices in operation, it is recommended that a rotary classifier be further developed into a laboratory standard. The following are proposed as preliminary features of a laboratory chunkwood classifier:

- A series of concentric screens producing five particle sortments plus fines.
- Circular or hexagonal screens.
- Interchangeable sets of screens each with different geometric openings; *i.e.*, round holes, square holes, and elongated slots.
- Screen openings with the following dimensions: 100, 75, 50, 25, and 5 mm.
- Tiltable screen assembly in 1-degree increments between 0 and 10 degrees.
- Variable speed control between 0 and 100 rpm.
- Separate unloading doors for each screen chamber.
- Optional provision for operating the classifier in a horizontal position with screen ends plugged, or in an inclined position with screen ends open.
- Optional batch loading into the inner screen chamber (about 6 cubic feet), or continuous loading of chunks into an inner screen chamber through a feed hopper.
- Timer for automatic shutoff.

Reduction

- If the general objective is to obtain a random mix of particles intermediate in size between normally produced chunkwood and conventional pulp chips, and there is no particular concern over the geometry of the individual particles, then a modified hammermill assembly could be incorporated into the design of the wood chunker. Thus, particles emerging from the wood chunker would have passed through the hammermill before discharge. An example application for the intermediate-sized particles is as a fuel in a combustor having fuel specifi cations similar to the hammermilled output from a chunker.
- If the general objective is to obtain a fairly homogeneous mix of particles having a general specified particle geometry, then a hammermill could be used at a mill or centralized processing location. A screening device would be used to sort the acceptable particles from the oversized and fines. Oversized particles would be recycled through the hammermill for further reduction. An example application is the production of elongated particles suitable for flaking in a ring flaker—the flakes would be used in the production of flakeboard or other composite flake products.

CONVERSIONS

1 foot = 30.48 centimeters
1 inch = 2.54 centimeters
1 pound = 0.4536 kilogram
1 cubic foot = 0.0283 cubic meter = 28.3206 liters
1 pound/cubic foot = 16.0184 kilograms/cubic meter
1 horsepower = 0.7457 kilowatt

LITERATURE CITED

Arola, Rodger A. 1984. **Chunking of small trees - an alternative to chipping**. In: Robertson, Doris, proc. coord. Harvesting the South's small trees; 1983 April 18-20; Biloxi, MS. Proc. 7340. Madison, WI: Forest Products Research Society: 117-127.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A. 1985. **Chunking bundled small-diameter stems**. Forest Products Journal. 35(4): 40-42.

Barnett, Paul E.; Sirois, Donald L.; Ashmore, Colin. 1986. **Reduction of biomass moisture by crushing/splitting - a concept**. In: Rockwood, Donald L., ed. Proceedings of the 1985 Southern forest biomass workshop; 1985 June 11-14; Gainesville, FL. Gainesville, FL: University of Florida, Institute of Food and Agricultural Sciences: 13-16.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. **Involuted disc slicer**. U.S. patent 4,431,039. February 14. 11 p. Int. Cl.^{3} B27L 11/02. U.S. Cl. 144/176.

Fuller, William S. 1985. **Particle size classification**. In: Robertson, Doris, proc. coord.; White, Julia, ed. asst. Comminution of wood and bark; 1984 October 1-3; Chicago, IL. Proc. 7336. Madison, WI: Forest Products Research Society: 203-212.

Sturos, John A. 1973. **Rotary screening to remove bark and foliage in the field**. The Northern Logger and Timber Processor. 21(11): 16-17, 38.

Chunkwood Drying Research With Northern U.S. Hardwoods[1]

Rodger A. Arola, Joseph B. Sturos, and Robert C. Radcliffe[2]

Abstract.—Three types of experiments involving storage and drying of chunkwood were conducted. Indoor exploratory experiments with convective and forced air drying demonstrated that small quantities of chunkwood either dried faster than conventional wood chips or required much less air horsepower in forced air systems. Follow-up outdoor drying experiments with chunks and chips stored in small cribs tended to support the hypothesis that chunks initially dry faster than chips. This can have important implications for scheduling inventories of wood fuel supplies and use. Experiments involving windrow pile drying of chunkwood showed that covered piles dry more completely and more uniformly than uncovered piles. Uncovered piles had a very wet outer layer and a drier inner core. With covered piles, there was no conclusive evidence that perforated vertical stacks with wind turbines enhanced chunkwood drying. The general conclusion is that large chunkwood particles placed in storage offer less resistance to the movement of air and the venting of escaping moisture than conventional wood chips.

INTRODUCTION

The most important inherent physical property that influences the energy content of wood fuels is moisture. Fortunately, moisture content can be readily reduced through artificial or induced means, or simply by relying on the wind and sun.

The relative ease in which wood fuel dries is closely related to the size of the individual fuel particles and to the level of resistance that the bulk material offers to the flow of air, whether air flow is forced as with fans or natural as with wind. In large, outdoor wood fuel storage piles, another important factor is the pile's natural ability to vent escaping moisture-laden air and replace it with drier, externally-drawn air.

The shape and size of wood fuel particles not only determine the distance that moisture must travel within each particle to get to the surface where it can evaporate, but they also directly influence air flow resistance of the bulk material and its ability to allow evaporating fuel moisture to escape.

Chunkwood particles are, on the average, much larger and much different in geometric shape

[1]*Paper presented at the International Energy Agency/ Bioenergy Conference, Task III/Activity 6 and 7 "Production, storage, and utilization of wood fuels." [The Swedish University of Agricultural Sciences, Uppsala, Sweden, December 6-7, 1988.]*

[2] *Rodger A. Arola, Joseph B. Sturos, and Robert C. Radcliffe are Research Mechanical Engineer, Mechanical Engineering Technician, and Electronic Technician, respectively, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

than conventional whole-tree chips (Arola *et al.* 1983) (fig. 1A). Chunkwood contains particles that are not only larger than typical chips, but are more equidimensional. Chunks are generally blocky pieces of wood; chips are flat, platy particles. We hypothesize that these obvious differences in particle size and shape are extremely important in determining which type of particle dries best.

The basic hypothesis is that larger chunkwood particles, when stored, will dry faster than smaller chips. Imagine that we have two outdoor storage piles of wood fuel. In one pile, the fuel particles are all the size and shape of bowling balls; in the second, they are the size and shape of playing cards. In the pile containing the bowling ball-size fuel particles, there would be large interparticle void spaces with very little

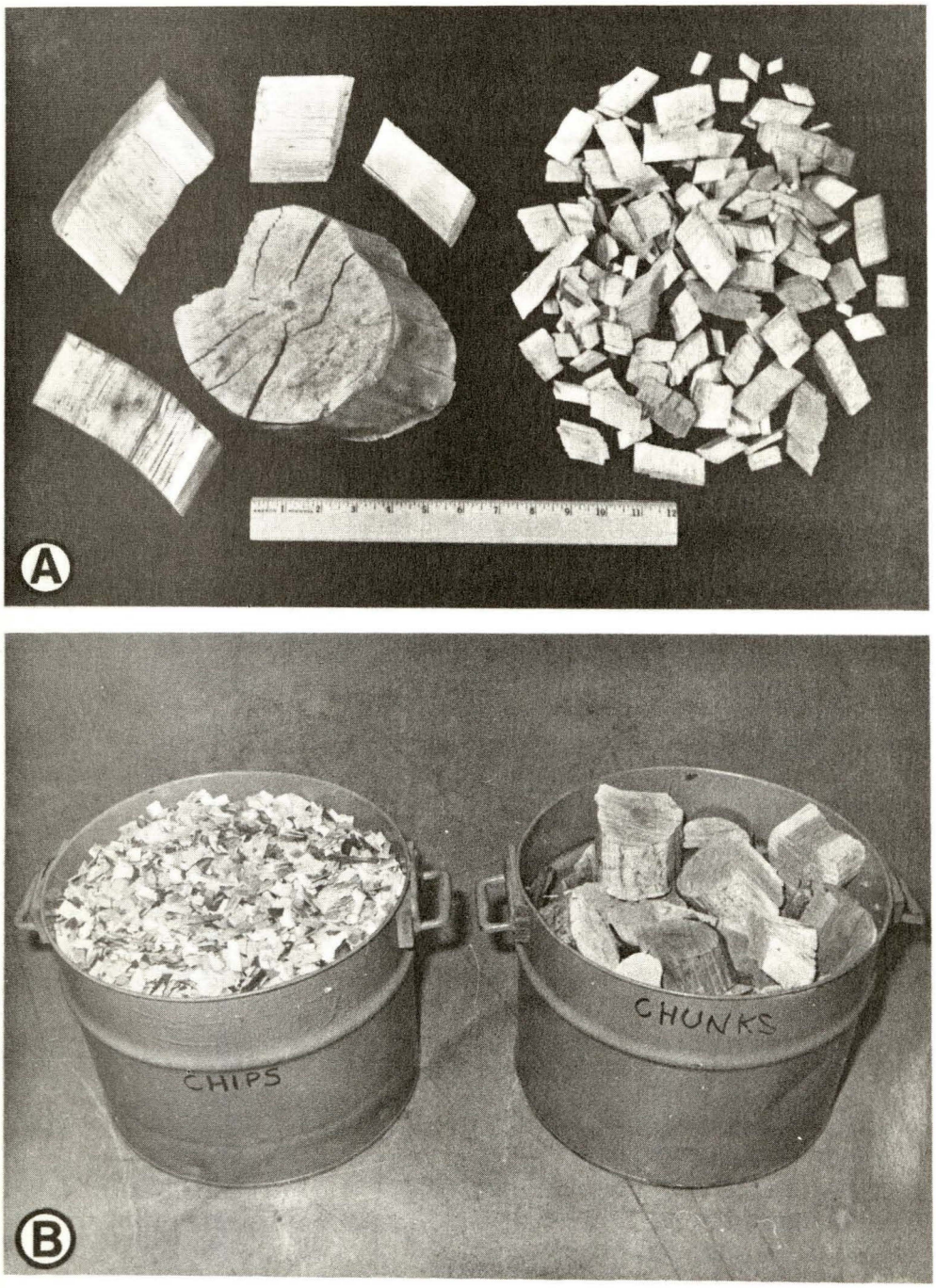


Figure 1.—*A. Typical chunks and chips. B. Test setup for exploratory indoor natural convective air drying.*

intimate particle-to-particle contact. There would be almost point contact. Rain on this pile would quickly percolate through it with very little being absorbed into the wood—not only because of limited retention time, but also because of limited contact area.

In the other pile, playing card-shaped particles would layer nearly horizontally on top of each other with a large amount of intimate contact and very small interparticle void spaces. Should rain fall on this pile, the water would percolate through slowly. The greater amount of particle surface area, intimate particle contact, small void spaces, and greater surface tension between the water and the surface of the particles would hinder the free movement of air, venting of evaporated moisture, and percolation of rain through the particles. This simplistic analogy will never actually happen, but it can show the influence of particle size and shape on air flow resistance, venting of moisture, and drainage of a bulk material in storage.

The objective of the work reported here was to document and/or compare the net reduction in moisture in chunkwood and chips in various storage/drying experiments. Our initial drying studies began indoors on an exploratory scale with small quantities of chunkwood and chips; larger scale follow-up studies were then conducted outdoors in small storage cribs and a windrow pile.

INDOOR DRYING EXPERIMENTS

Two small-scale exploratory drying experiments were conducted to determine if chunks or chips dried at the same or different rates when subjected to the same ambient conditions (Sturos 1984a, Sturos *et al.* 1983). One experiment involved natural convective air drying, and the other used forced air drying. Both were conducted indoors using ambient room air.

Convective Drying

For the indoor convective air drying experiment, equal volumes of green chunks and chips made from clean bolts were placed in separate 3.6-cubic foot cylindrical containers (1/2 of a 55-gallon barrel) and left in an open room to dry freely (fig. 1B). Both aspen (*Populus tremuloides*) and red maple (*Acer rubrum*) chunks and chips were dried in this manner. Each container was periodically weighed to monitor moisture loss (fig. 2). Ambient temperature and relative humidity were recorded at each weighing.

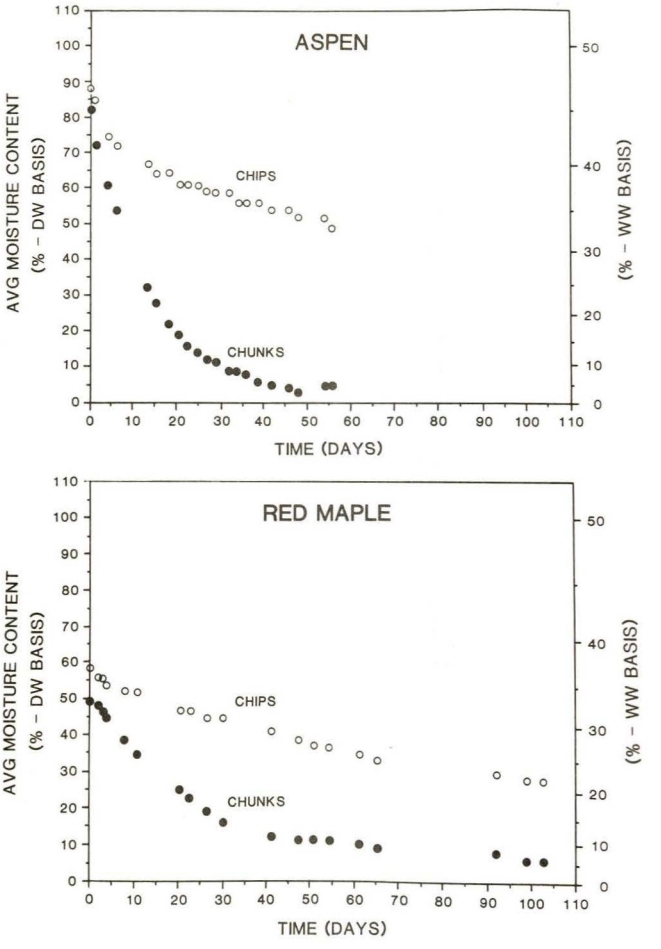


Figure 2.—*Drying curves for indoor natural convective air drying of aspen and red maple chunks and chips.*

The aspen test ran for 55 days during which time the air temperature averaged 73 degrees F and ranged between 65 degrees F and 83 degrees F. The relative humidity averaged 36 percent, with a range of 18 to 54 percent. The red maple test ran 103 days. The temperature averaged 75 degrees F and ranged between 66 degrees F and 89 degrees F. The relative humidity averaged 60 percent with a 35 to 64 percent range.

With both aspen and red maple, the chunks dried quicker and to a lower moisture content (MC) than the chips. The aspen chunks reached a minimum MC of 5 percent in 41 days, whereas the aspen chips reached only 35 percent in the same time. (All MC's are on a wet-weight basis unless otherwise noted. Moisture content is graphically presented on both a wet- and dry-weight basis for the convenience of the reader accustomed to one or the other.) In 100 days, red maple chunks reached an MC of 6 percent; the chips dried to 22 percent.

Forced Air Drying

For the forced air drying tests, a blower system forced ambient room air through each bulk material (fig. 3). Separate 7.3-cubic foot cylindrical containers (standard 55-gallon barrel) with

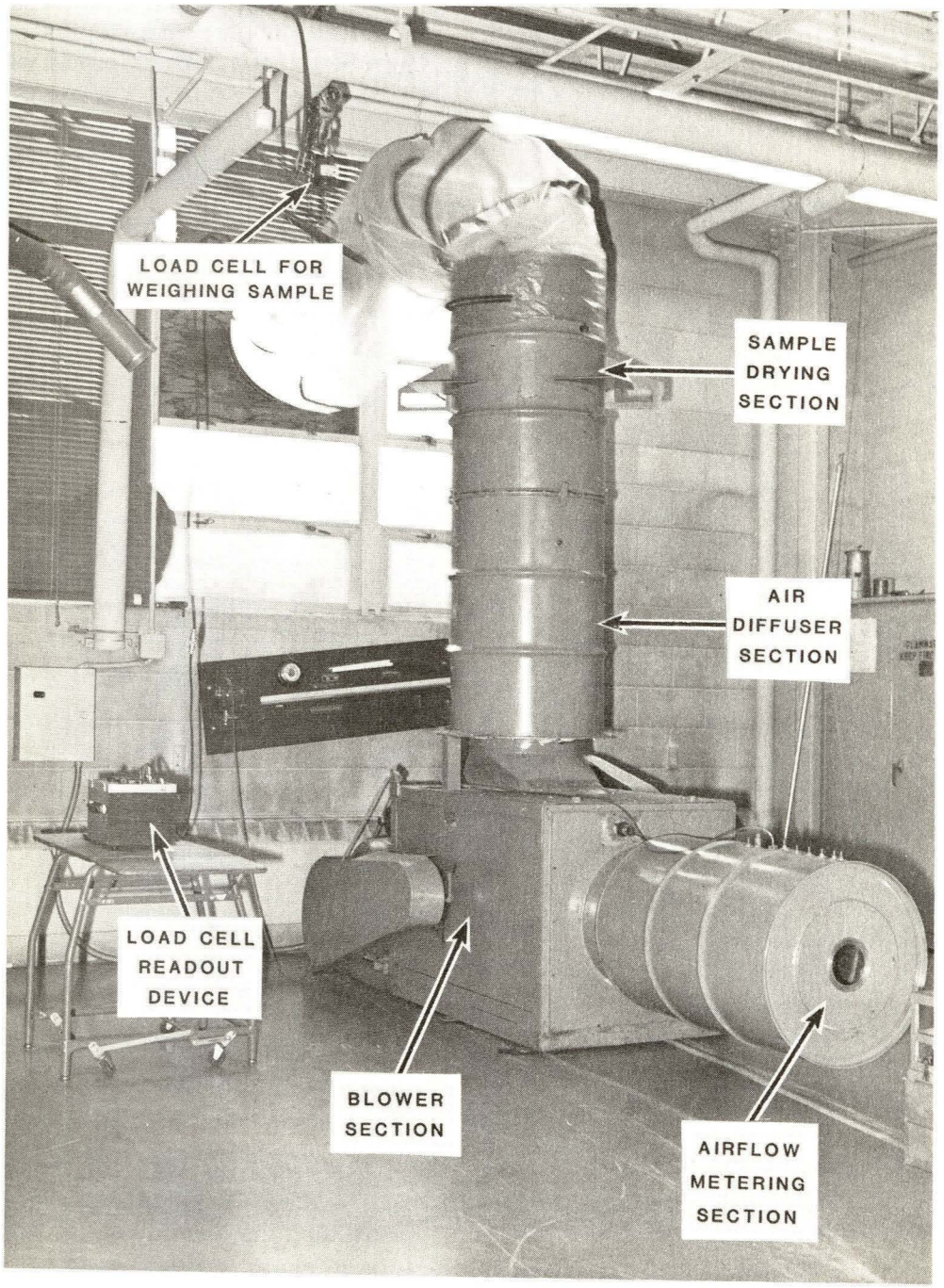


Figure 3.—*Test setup for exploratory indoor forced air drying.*

screened bottoms were filled with chunks and chips. Room air delivered at a nominal rate of 340 cubic feet per minute (cfm) (123 cfm per exposed square foot) was used to dry the particles. (The 340-cfm level was used because it was the lowest practical level at which the particular blower system used would operate and not because it was optimum for drying.) Five repetitions were made with equal sample weights of chips and chunks dried alternately.

Under forced ambient room-air conditions stated, the chips dried faster and to a lower MC (fig. 4). However, in doing so, they required much more back pressure to maintain the 340-cfm air flow.

This higher back pressure translated into more blower energy (power x time) to force air-dry chips versus chunks. In these experiments, aspen chips dried to 20 percent residual moisture required 74 percent more blower energy than chunks. Red maple chips used 44 percent more energy than chunks to dry to the same 20 percent moisture level (fig. 5).

Later research conducted to determine resistance to air flow showed that chunkwood developed from 40 to 77 percent less pressure drop across a given bed depth than chips did with air flow rates in the range of 50 to 1,000 cfm (Sturos 1989).

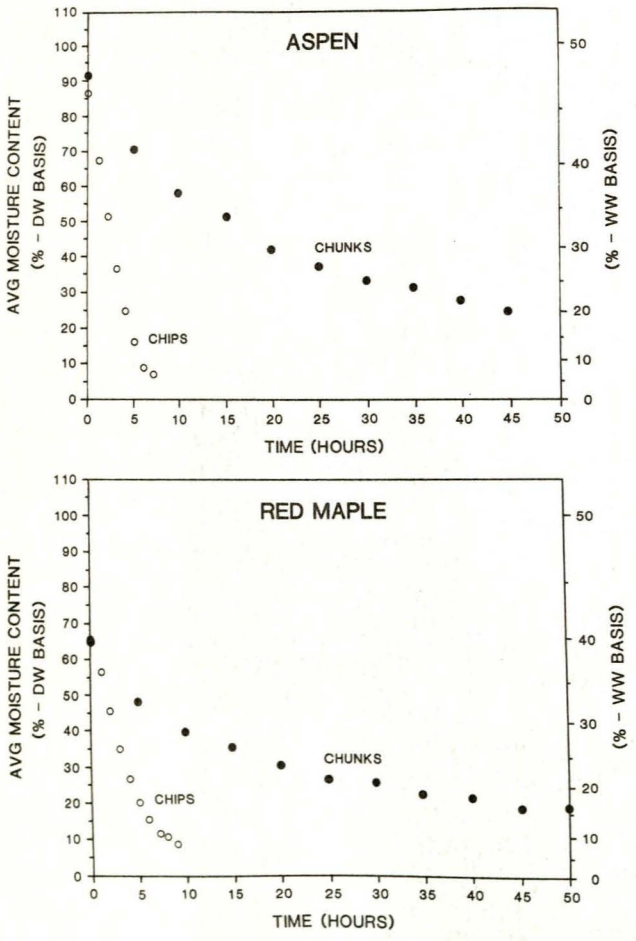


Figure 4.—*Drying curves for indoor forced air drying of aspen and red maple chunks and chips. (Based on the average of five repetitions.)*

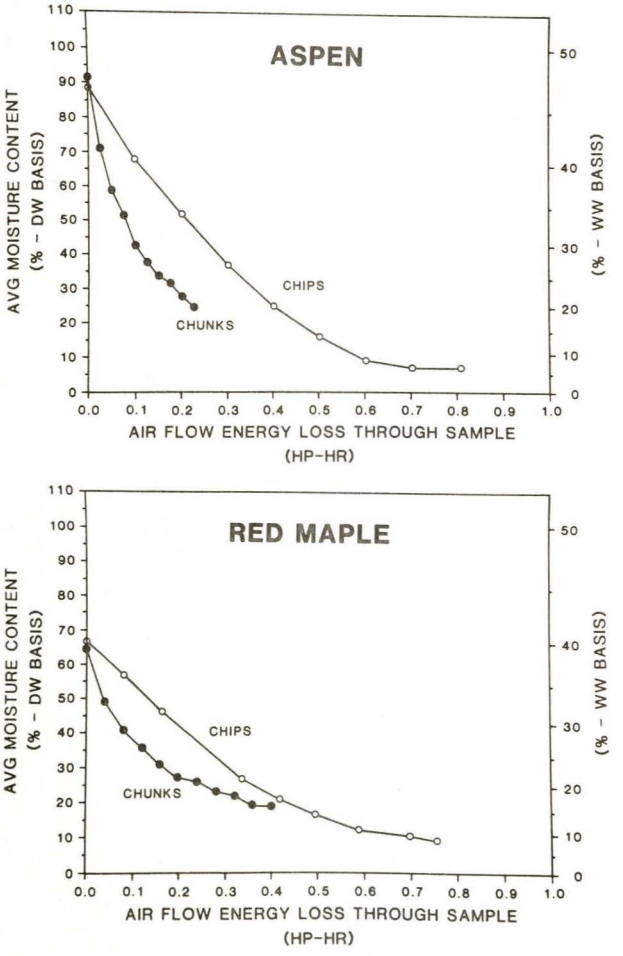


Figure 5.—*Energy used in indoor forced air drying of aspen and red maple chunks and chips. (Based on the average of five repetitions.)*

OUTDOOR CRIB DRYING EXPERIMENTS

The positive results with chunkwood in these indoor drying experiments justified an outdoor containerized drying study to compare the rate of drying of chunkwood and chips when stored under conditions of a more practical scale for small wood fuel users, such as farmers.

Methods

The storage containers used in this study were identical, 256-cubic foot cribs (Sturos 1984a, 1984b) (fig. 6). Each crib, 4 feet wide, 8 feet long, and 8 feet high, had 1/2-inch-wide ventilation slots spaced 5-1/2 inches apart in the floor bottom, 1/2-inch mesh screening on the sides,

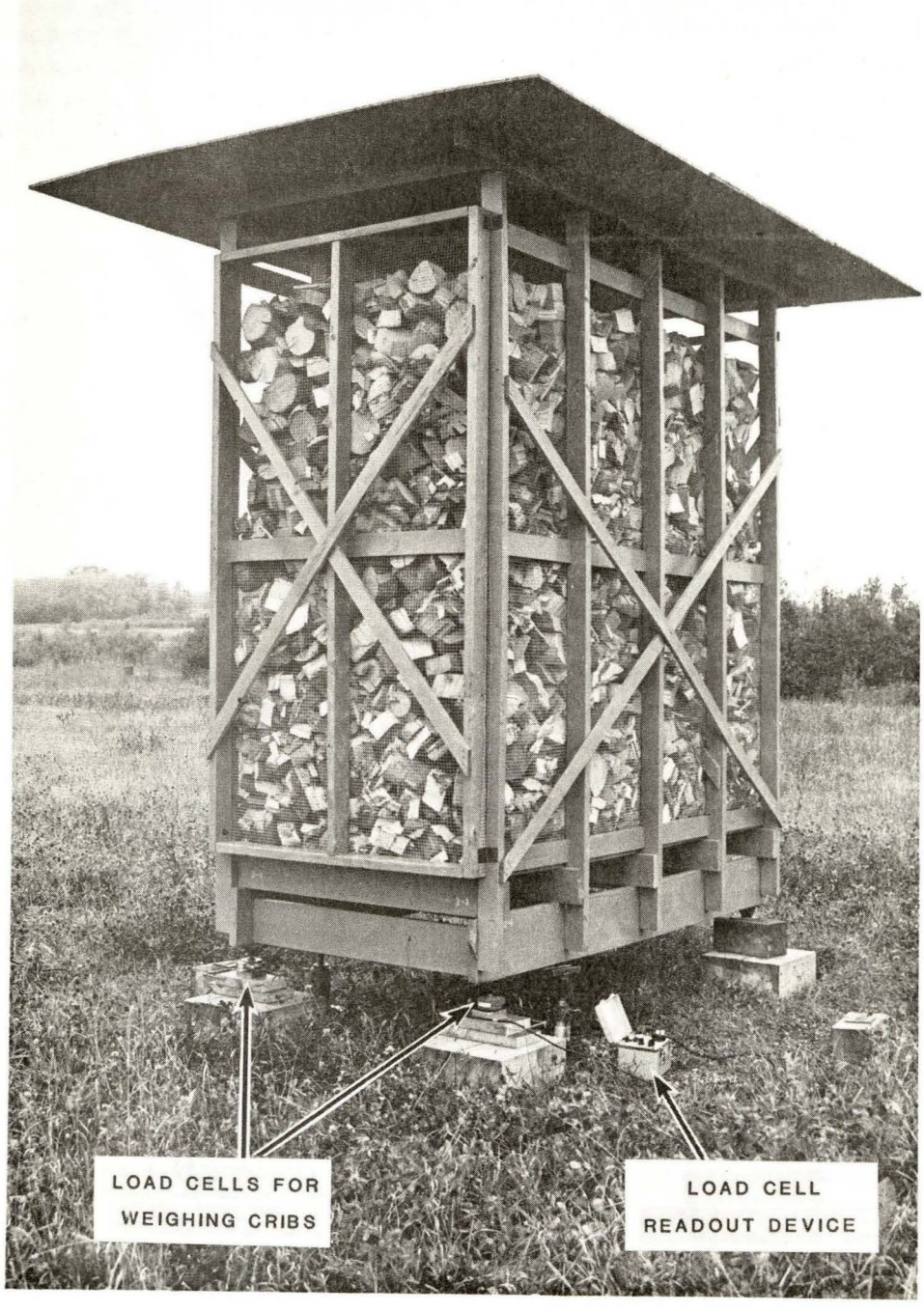


Figure 6.—*Test setup for outdoor crib air drying experiment.*

and an 8- by 12-foot roof. Eight cribs were fabricated. For aspen, two cribs were filled with chunks and two were filled with chips—this basic four-crib experiment was then repeated for sugar maple (*Acer saccharum*). This gave two replications per species for chunks and chips. The cribbed chunks and chips were placed in a large open field to dry.

The beginning MC of the material contained in each crib was determined. The cribs were weighed weekly to determine weight (moisture) loss. Subsequent MC's were based on the original weights, initial MC's, and weekly weight measurements.

The basic study period lasted from early July through late October. The actual sugar maple test continued for 110 days, during which time the temperature averaged 56 degrees F and ranged from 31 to 75 degrees F. The relative humidity averaged 82 percent and ranged from 58 to 100 percent. Precipitation totaled 16 inches.

The aspen test began 19 days after the sugar maple test and continued for 91 days. The temperature averaged 55 degrees F and ranged from 31 to 74 degrees F. The relative humidity averaged 83 percent with a 58 to 100 percent range. The precipitation totaled 11 inches.

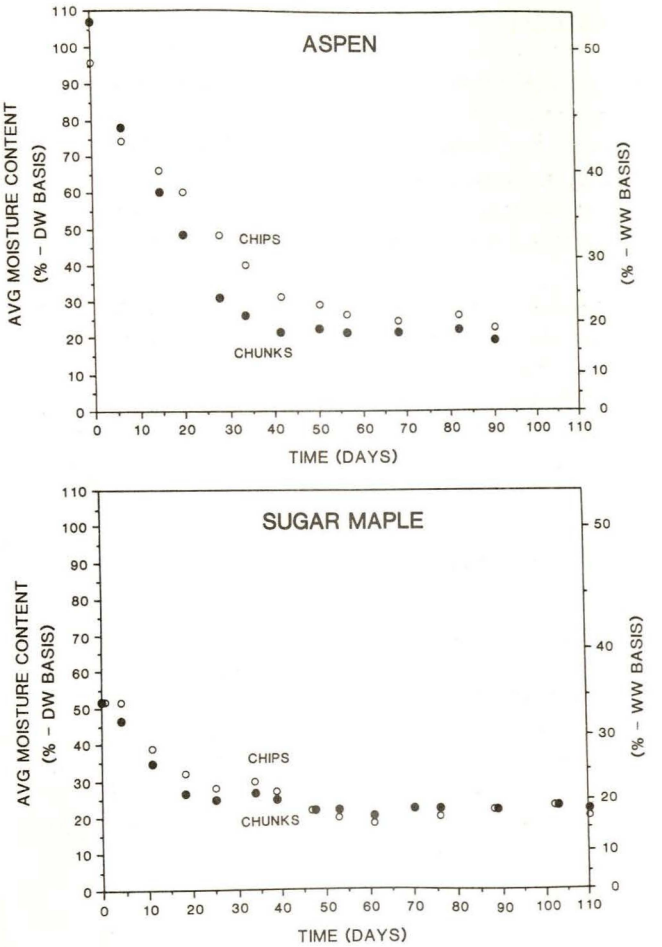


Figure 7.—*Drying curves for outdoor air drying of aspen and sugar maple chunks and chips. (Based on the average of two replications.)*

Results

The MC of sugar maple chunks dropped from 34 percent on a wet-weight basis to 17 percent in 61 days, and then fluctuated between 18 and 19 percent for the remainder of the test (fig. 7). The standard deviation for the variation between replications was 0.6 percent. In comparison, the MC of sugar maple chips dropped from 34 percent to 15 percent in the same 61 days, and then fluctuated between 17 and 19 percent for the remainder of the test. The standard deviation for the variation between replications was 0.5 percent. There was no suggested practical difference between the minimum moisture levels for chunks and chips over the approximate 2-month period. In fact, one could logically assume that both chunks and chips would eventually come to about the same equilibrium moisture content given enough drying time. What is suggested as being important, assuming both chips and chunks start at nearly the same moisture content, is that these two materials have different characteristic drying paths.

The graphical display of outdoor crib drying data for aspen showed a distinct separation of the drying plots, which supports the hypothesis that chunks dry faster than chips during the first several weeks of storage (fig. 7). The drying data for sugar maple do not show such a clear separation. It should be noted that 3-1/2 inches of rain fell during the first 4 days of storage of sugar maple chunks and chips. The chips showed no drying, but the chunks actually lost about 5 percentage points in moisture.

From the crib drying experiments, it would appear that chunks initially dry faster than chips. This can be an important advantage of chunks. For example, by interpolating the data for aspen, after 30 days of crib storage the chunks dropped to almost 20 percent moisture (wet-weight basis) compared to 30 percent for the chips. If we look at the data in another way, it took about 1 month for the chunks to drop to 20 percent MC, whereas the chips took almost 2 months. Although the chunks began at a slightly higher moisture level than the chips, the chunks overtook the chips after 10 days and then continued to dry at a higher rate during the initial 30 days.

WINDROW DRYING EXPERIMENT

The purpose of the windrow drying experiment was to document moisture reduction in chunkwood when stored in a reasonably large pile. Three windrow storage treatments were investigated. The treatments were: (a) an uncovered pile section, (b) a covered section, and (c) a covered section having tubular vent stacks with attached wind turbines (fig. 8).

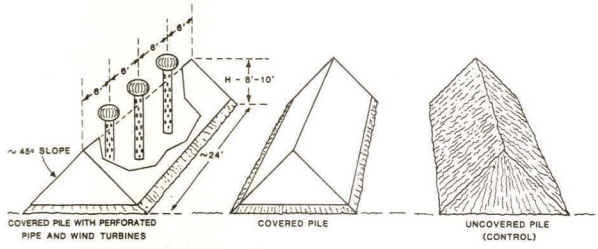


Figure 8.—*Three windrow pile treatments for drying chunkwood.*

Methods

The chunkwood was produced from mixed northern hardwoods, principally red maple. The chunks were produced with the USDA Forest Service involuted single-disc experimental wood chunking machine built in Houghton, Michigan (Barwise *et al.* 1984). The finished pile was about 75 feet long with tapered ends and about 8 feet high. The entire pile contained about 120 tons (green-weight basis) of chunks. Chunking began in June, but the pile was not completed until July. The entire pile was left undisturbed throughout the summer (when maximum drying should occur). The pile was broken up in mid-October. At that time, the prebagged samples of chunks were retrieved and analyzed for MC.

The uncovered pile was the control. It was subjected to the elements—sun, wind, rain, and an early October snow. A second pile was covered with a nylon reinforced plastic sheet that covered all but the lower few feet from ground level. The covering was tied down directly on top of the pile with no air chamber between the covering and the chunkwood. A third pile, also covered with the same material, had three perforated tubes inserted vertically at the quarter points of that test section. The tubes protruded about 2 feet from the top of the pile. Small wind turbines attached to the top of each perforated tube rotated in even the slightest breeze. The anticipated benefit of the wind turbines was that they would force the exchange of air and speed the drying by allowing moisture-laden air to escape through the turbines as new air was drawn in from the uncovered region near the bottom of the pile. This would be accomplished with no expenditure of inputted energy other than from the wind.

During construction of the windrow, mesh bags containing representative samples of chunkwood were placed as near as possible to preestablished locations in the pile (fig. 9). The scheme illustrated shows 12 sample bags located throughout a transverse triangular cross section. The outer shell area as illustrated had three times the area as the inner core (shaded zone). For this reason, three times as many sample bags were located in the outer shell as in the inner core. Within each treatment section of the pile, there were two transverse planes each containing bags of chunks located according to the scheme described. Thus, there were two replications per pile treatment. The transverse planes were located at the third points of each treatment section. The values reported in the following discussion of test results are based on MC averages for the two matching bags at the two transverse locations within the pile.

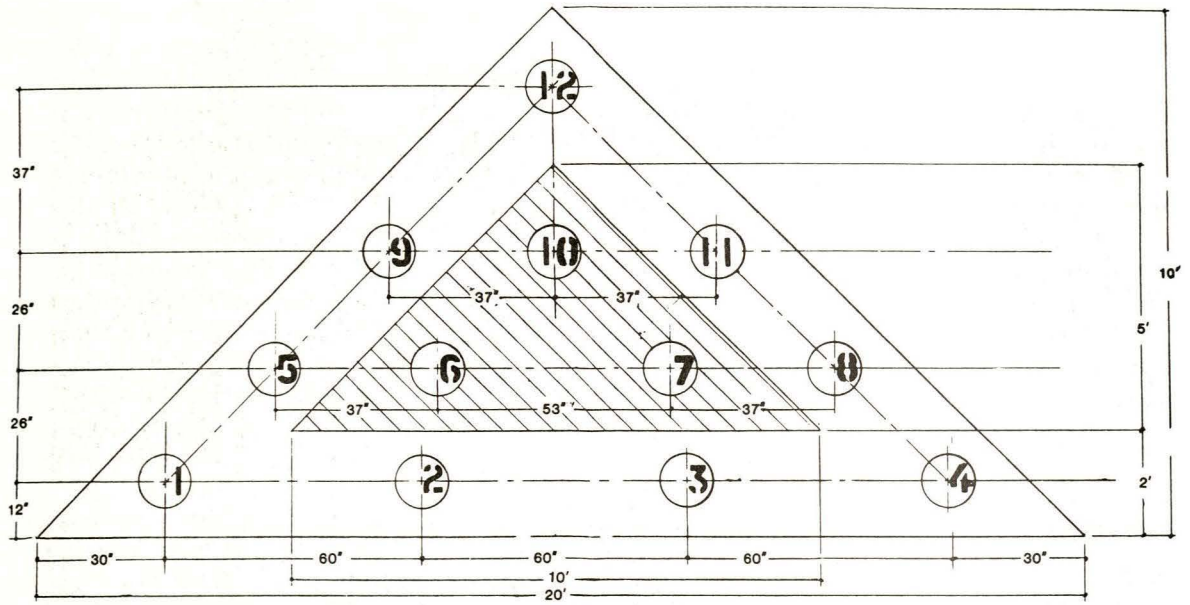


Figure 9.—*Transverse pile locations of bags of chunkwood for moisture content determinations.*

The windrow was constructed parallel to an adjacent dirt road in a field clearing. The nearest trees at the edge of the clearing were about 100 feet away. The pile orientation was for convenience of construction and esthetic appearance on the private owner's land. The finished pile was oriented at 57 degrees to the west of due north. This gave the southwestern side of the pile predominant exposure to the sun, and the northeastern side more exposure to prevailing winds from the northwest to northeast. (No attempt was made to document localized disturbances in the wind direction caused by the trees or site topography.)

Results

Laboratory personnel, not equipped to do commercial logging, took about 1 month to harvest the trees, produce the chunks, and construct the windrow pile (fig. 10A). For experimental control, it would have been desirable to do all of these operations in a few days, but this was not possible. To obtain the average MC of the green wood going into the pile, random samples of chunkwood were periodically collected and analyzed for moisture as the pile was being constructed. The mean initial MC of the chunkwood based on 41 observations was 37 percent (green-weight basis). The standard deviation about the mean was 2.5 percent. After about 3-1/2 months of storage, the piles were torn apart, the mesh bags containing the chunks were retrieved, and MC's were determined.

Uncovered Pile

The chunks in the uncovered pile dried the least. When this pile section was dismantled, it was apparent that the pile had two distinctly different zones—an outer shell and an inner core. The chunks in the outer shell were blackened, slimy, and wet. Those in the inner triangular core were clean in appearance and much drier (fig. 10B). The mean MC of the chunks located in the outer shell was 45 percent (fig. 11). These chunks actually gained, on the average, 7 percentage points in moisture. The chunks in the inner core lost 10 percentage points in moisture so that the final mean MC was 27 percent. The mean MC for the entire uncovered pile was 38 percent, showing there was no overall net reduction in moisture. For the size of our test windrow, the net gain in moisture in the outer shell cancelled the

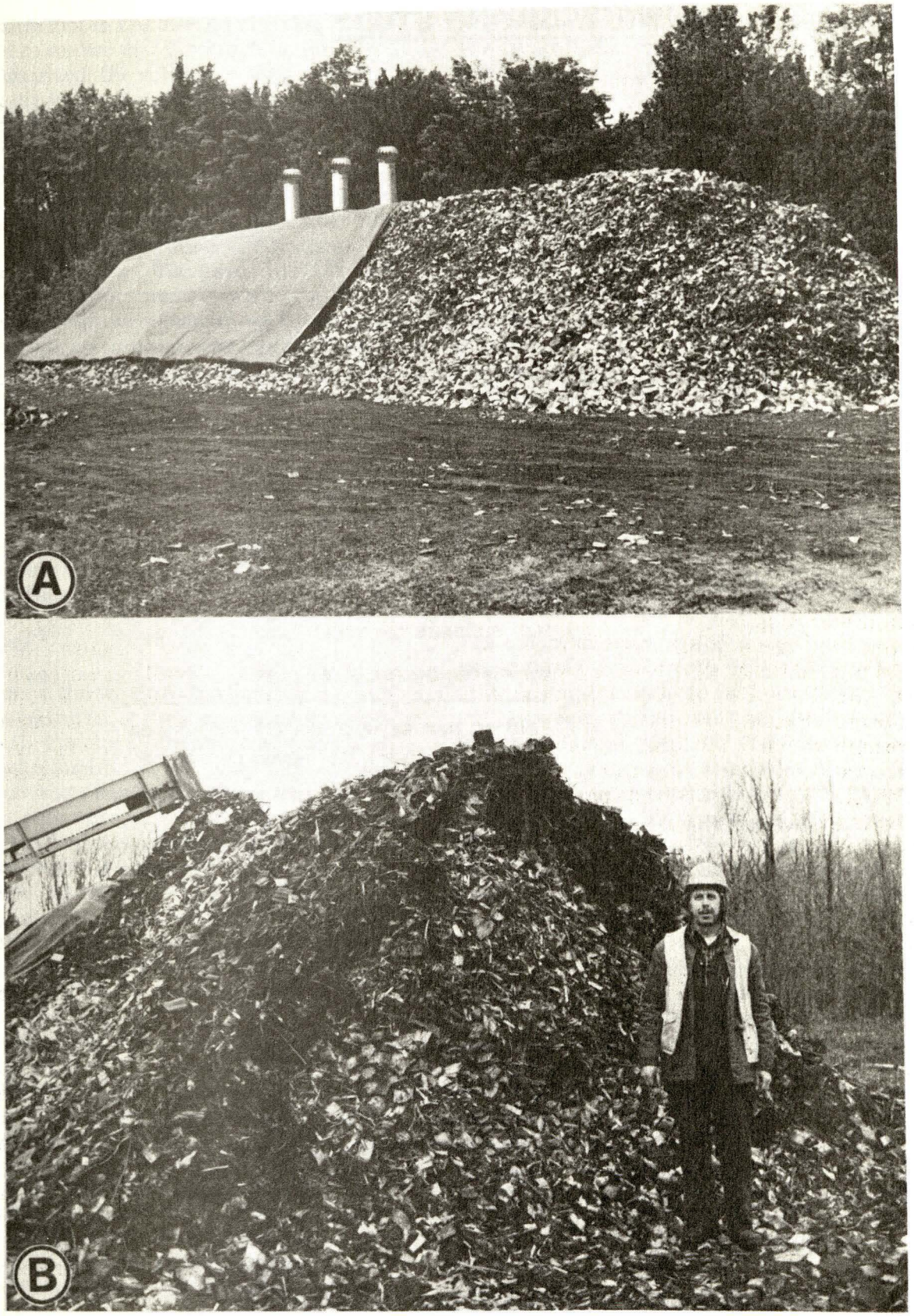
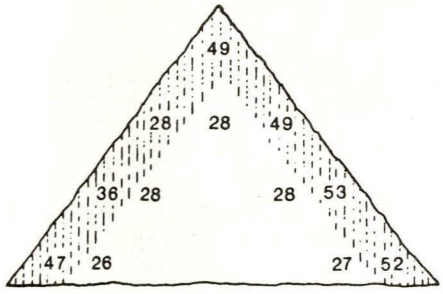


Figure 10.—*A. Finished windrow pile. B. Transverse sections through uncovered pile after dismantling.*

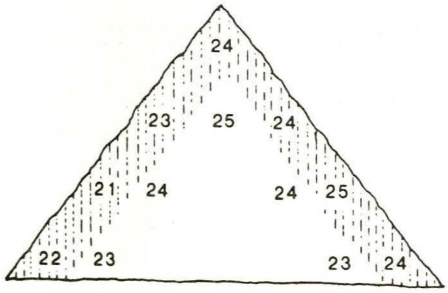
WINDROW DRYING STUDY



UNCOVERED PILE

	MEAN	STD. DEV.	MEAN M.C. BY LEVEL
OVERALL M.C. (%)	38	12	49
M.C. SURFACE ONLY (%)	45	10	35
M.C. INTERIOR ONLY (%)	27	2	36
			38

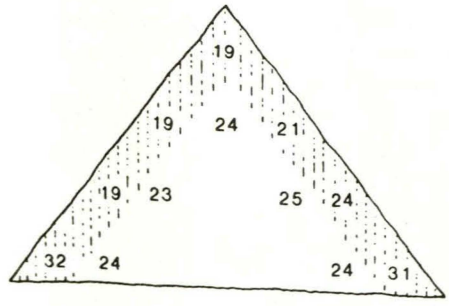
SIG. DIFF. BETWEEN SURFACE AND INTERIOR BASED ON GROUP T-TEST @ 95% CONFIDENCE LEVEL.



COVERED PILE

	MEAN	STD. DEV.	
OVERALL M.C. (%)	24	1	24
M.C. SURFACE ONLY (%)	23	2	24
M.C. INTERIOR ONLY (%)	24	1	24
			23

NO SIG. DIFF. BETWEEN SURFACE AND INTERIOR BASED ON GROUP T-TEST @ 95% CONFIDENCE LEVEL.



COVERED & VENTED PILE

	MEAN	STD.DEV.	
OVERALL M.C. (%)	24	4	19
M.C. SURFACE ONLY (%)	24	6	22
M.C. INTERIOR ONLY (%)	24	1	23
			28

NO SIG. DIFF. BETWEEN SURFACE AND INTERIOR BASED ON GROUP T-TEST @ 95% CONFIDENCE LEVEL.

Figure 11.—*Drying results from three windrow storage treatments.*

net moisture lost in the interior chunks. (It is important to realize that if a much larger pile were constructed, the volume of chunks contained in the inner triangle would be different from our test pile.)

The chunks in the outer shell also showed a much greater variability in final MC as indicated by the standard deviation about the mean value—10 percent in the outer shell versus 2 percent in the interior. The mean MC is also indicated for the four height levels in the pile where sample bags were located—although there was variability, no trend can be reported. An analysis of variance of the MC of the bags located on the northeast side of the pile compared to the MC of bags on the southwest side showed a significant difference at the 98 percent confidence level. The chunks on the southwest side were consistently drier. Only a possible explanation for this can be offered. The southwest side of the pile had more exposure to the sun; the northeast side was subjected more to driving heavy rains and snow.

Covered Pile

The section of the windrow having only a covering exhibited the most uniform drying throughout (fig. 11). For the entire pile, there was a 13 percent net reduction in the mean MC—the final mean value was 24 percent. There was no significant difference in MC between chunks in the outer shell versus those in the interior—the standard deviations were only 1 and 2 percent, respectively. The mean MC's at the four levels in the pile also showed uniform drying throughout. The chunks contained in this pile were clean in appearance compared to the black, slimy chunks in the outer shell of the uncovered pile.

Covered and Vented Pile

As with the covered pile, there was no significant difference in drying between the outer surface and the interior chunks (fig. 11). The mean final MC for the entire pile was 24 percent. The surface and interior chunks had the same mean value. There was, however, more variability in moisture in the surface chunks as indicated by the higher standard deviation compared to that of the interior chunks. The vented pile had point locations with lower MC's than either of the other two treatments. For an unexplained reason, the MC was much higher in the chunks located at the lower outer edges than anywhere else in the pile. The chunks in this section of the pile also appeared much cleaner than in the uncovered pile.

The mean results of the windrow drying study are summarized in the following tabulation:

	Mean MC	Coefficient of variation
	(Percent)	
Covered	24	5.6
Covered and vented	24	16.8
Uncovered	38	30.8

As indicated by the coefficient of variation, the covered pile dried most uniformly. As previously noted, the beginning mean MC for all chunks in the pile was 37 percent.

DISCUSSION AND RECOMMENDATIONS

The indoor convective and forced air drying experiments were strictly exploratory in nature, and the conditions were far from ideal or practical. However, in spite of these shortcomings, two key conclusions resulted. The first was that the large chunks appeared to dry faster than the much smaller, flat wood chips under natural convective air drying conditions. The most important conclusion from the forced air drying experiment was that it took much more blower energy to force air through a depth of chips than through an equal depth of chunks.

The outdoor crib drying experiments approached a scale that could be considered practical for small wood fuel users. Data from our crib drying study tended to support the hypothesis that chunkwood dries at a faster initial rate than conventional fuel chips during the first month or two after being placed in storage. This observation was especially true with aspen but not quite so obvious with sugar maple. This can be an important potential advantage of chunkwood if the fuel is consumed at a rate falling within this time frame. Assuming both start at nearly the same MC, the chunks would dry to a lower MC within the first month or so compared to chips.

If the chunks and chips are stored long enough, they would both reach about the same equilibrium MC, and the potential drying advantage of chunks would diminish.

Several important conclusions were reached from the windrow drying study. First, chunkwood stored in an uncovered pile during the summer exhibited two distinctly different drying zones. The chunks contained in the outer shell, about 18 to 24 inches thick, were as wet or wetter than when placed into storage, and were blackened and slimy. (This, of course, depends on the amount of rainfall.) Compared to those in the outer shell, the chunks located in the inner core of the pile were much drier and appeared much like they did when first placed into storage.

Outdoor chunkwood storage piles in areas with moderate to heavy precipitation should be covered to maximize drying. The cover should be made of a durable material having ultraviolet protection to minimize degradation of the cover by the sun. Chunkwood stored under cover will dry relatively uniformly throughout. There was no obvious benefit to providing tubular stacks with attached wind turbines in addition to the pile covering. However, this approach was insufficiently investigated to make definite conclusions about the benefits of wind turbines. Further work should be done to compare the drying characteristics of chunkwood in storage piles both with and without vent stacks with wind turbines. So as not to confound the drying results for each experimental treatment, we recommend that separate piles be constructed so adjacent sections from a single pile do not interact with each other.

The outdoor pile drying data of chunkwood as reported in this study are based on summer storage. No inferences can be made about drying in winter storage. Such a study should be conducted—preferably with the same three treatments included in this study.

CONVERSIONS

1 foot = 30.48 centimeters
1 inch = 2.54 centimeters
1 pound = 0.4536 kilogram
1 cubic foot = 0.0283 cubic meter = 28.3206 liters
1 gallon = 3.7853 liters
1 ton (2,000 pounds) = 907.194 kilograms = 0.9072 tonne
Fahrenheit = 1.8 (Celsius) + 32.

LITERATURE CITED

Arola, Rodger A.; Winsauer, Sharon A.; Radcliffe, Robert C.; Smith, Martyn R. 1983. **Chunkwood production: a new concept**. Forest Products Journal. 33(7/8): 43-51.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. **Involuted disc slicer**. U.S. patent 4,431,039. February 14. 11 p. Int. Cl.^{3} B27L 11/02. U.S. Cl. 144/176.

Sturos, Joseph B. 1984a. **Ambient air drying trials—chunkwood versus chips**. In: Biomass fuel drying conference proceedings; 1984 August 8-9; Superior, WI. St. Paul, MN: University of Minnesota, Office of Special Programs: 17-35.

Sturos, Joseph B. 1984b. **Characterization and air drying of chunkwood and chips**. Res. Note NC-308. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 6 p.

Sturos, Joseph B. 1989. **Airflow resistance of chunkwood**. Forest Products Journal. 39(3): 19-24. (Also in: 1988. Airflow resistance of chunkwood. In: Production, storage and utilization of wood fuels: Proceedings of IEA/BE conference task 3/activity 6 and 7; 1988 December 6-7; Uppsala, Sweden. Res. Notes 133/1988. Garpenberg, Sweden: The Swedish University of Agricultural Sciences, Department of Operational Efficiency: 1: 181-194.)

Sturos, Joseph B.; Coyer, Lynne A.; Arola, Rodger A. 1983. **Air drying of chunkwood and chips**. Res. Note NC-293. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.

Forest Roads Built With Chunkwood[1]

Rodger A. Arola, Ralph J. Hodek, John K. Bowman, Gary B. Schulze[2]

Abstract.—The USDA Forest Service builds and maintains thousands of miles of single-lane gravel roads while carrying out the programs and activities necessary for managing national forest lands. Conventional roadbuilding gravel and aggregate are often completely lacking or are in short supply within an economical transport distance. Chunkwood, a recently introduced form of comminuted wood from whole trees, was investigated as an alternative material for building low-volume forest roads to serve the needs of the Forest Service and the logging industry. About 2.5 miles of roads were built at four different locations on the Chequamegon National Forest. The sites represented typical forest roadbuilding situations: a swamp crossing, a uniformly-graded sand, a fine-grained soil with a high water table, and an existing road with large mud holes. Numerous test sections were built involving only chunkwood, or chunkwood in assorted combinations with nonwoven geotextile roadbuilding fabric and gravel. Following construction, the roads were field tested, and data were gathered to evaluate the performance of the various road test sections. A tandem-axle dump truck loaded with sand with a gross weight of about 50,000 pounds served as the test vehicle. Field measurements included road rutting, lateral shoving, stiffness, and general settlement. Complementary laboratory testing of chunkwood was done to evaluate its compressibility, compactability, and permeability. The principal conclusion from both the field and laboratory research was that chunkwood is a viable alternative roadbuilding material. It possesses certain unique physical properties that make it superior to gravel under certain conditions. Chunkwood effectively stabilizes unpaved roadways, and its light weight is a major advantage. Chunkwood is amenable to the laboratory determination of engineering and behavioral characteristics. When these characteristics are fully understood, rational roadway design procedures can be developed for chunkwood just as they have been for natural soil and rock.

INTRODUCTION

In fiscal year 1987, the USDA Forest Service built or reconstructed about 8,000 miles of arterial, collector, and local roads on national forest lands. In total, they currently maintain about 340,000 miles of these three classes of forest roads. The majority of the road system is made up of single-lane, low-standard roads. The design, construction, maintenance, and operation of this extensive network of forest roads is

[1]*Paper presented at the International Energy Agency/Bioenergy Conference, Task III/Activity 6 and 7 "Production, storage, and utilization of wood fuels." [The Swedish University of Agricultural Sciences, Uppsala, Sweden, December 6-7, 1988.]*

[2]*Rodger A. Arola is Research Mechanical Engineer, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan; Ralph J. Hodek is Associate Professor, Department of Civil Engineering, Michigan Technological University, Houghton, Michigan; John K. Bowman is Forest Engineer, Tongass-Sitkine Area National Forest, USDA Forest Service, Petersburg, Alaska, formerly of Chequamegon National Forest, USDA Forest Service, Park Falls, Wisconsin; and Gary B. Schulze is Zone Materials Engineer, Superior National Forest, USDA Forest Service, Duluth, Minnesota.*

essential to the Forest Service for carrying out its programs and activities associated with multiple-use management of national forests.

Within national forest boundaries, the largest user-class is trucking to support logging operations. Depending on state legal load limits, loaded logging trucks weigh between 80,000 and 160,000 pounds. Logging trucks, with high axle loadings, are the most demanding of forest roads because of the high concentrated wheel loads and repetitive stresses transmitted to the roadway. Another major user is the public for recreational purposes. Regardless of user-class, serious road performance problems can arise when forest roads are built on soils having poor load-bearing capacity. Quite often forest roads must be built on sites that are the most difficult and least desirable for road construction. Examples include: extremely wet soils with high clay content; organic soils typically found in swamps, peat bogs, and muskeg; and uniformly-graded sands.

The commonly used term "low-volume roads" often connotes poor quality, low cost, and temporary use. Whether this perception is totally accurate is debatable. For purposes of this paper, a low-volume forest road is single-lane, unsurfaced, supports an average traffic of less than 100 vehicles per day, and generally has a short useful life. Perhaps a more accurate term is low-traffic-volume roads. For simplicity, the already established and more conventional term, low-volume roads, will be used in this paper.

Conventional roadbuilding materials (pit-run gravel and crushed aggregate) are preferred for most forest roadbuilding situations. But these materials are not always abundantly available within an economical transport distance. When available supplies are scarce, and forest roads of various standards must be built, it is reasonable to ration or reserve the high-quality roadbuilding materials for the higher quality roads. These materials, because they are extremely heavy, also cause problems where the ground simply cannot support the dead weight of the roadway above. Thus, the Forest Service or any other agency involved with building low-volume forest roads, including the military, is vitally interested in new or alternative roadbuilding materials.

One such material, which was recently introduced by Forest Service researchers, is chunkwood (Arola 1984, Arola *et al.* 1985, Barwise *et al.* 1984). Originally developed for use as a form of biomass fuel and as a raw material feedstock for manufacturing structural flakeboard, chunkwood has been the recent focus of a cooperative research and demonstration program to explore its use as an alternative forest roadbuilding material. The organizational participants in this cooperative program, as represented by the co-authors of this paper, were Michigan Technological University and the Forest Service (North Central Forest Experiment Station and the Chequamegon and Superior National Forests).

PRIOR WORK

Several researchers have investigated the use of whole-tree chips and sawdust for road building. Wood chip fills were used successfully on three wetland crossings on the Chequamegon National Forest in Wisconsin (Bowman *et al.* 1987). The general conclusion was that the wood chip fills placed on a peat base performed satisfactorily. Although the initial cost was about the same as that for soil fill, reduced deflection of the peat mat with the lightweight wood chip fill was believed important in reducing future maintenance cost and environmental damage.

Both sawdust and bark chips were successfully used on the Mt. Baker-Snoqualmie National Forest to stabilize road embankments and slide areas (Petersen *et al.* 1981). Besides its low cost, sawdust in place of soil reduced the unit weight by as much as 75 percent. Sealing the sawdust with emulsified asphalt extended the projected life expectancy to at least 15 years.

Paper mill sludge was also tested to stabilize loose sand roads in aggregate deficient areas (Lidell and Bowman 1987). This treatment gave a stable all-weather road and reduced erosion. Their recommendation was that sludge could be used on lower-standard collector and local roads if aggregate is not available.

Although both sawdust and wood chips were successfully used in forest road construction, their uniform small particle size and flat shape

present some disadvantages in terms of structural strength and life expectancy. With its wide range of particle sizes and blocky angular shape, chunkwood has characteristics that more closely resemble pit-run gravel. Chunkwood particles tend to mat into an interlocking matrix with good vertical and lateral strength. The above characteristics appear to make chunkwood superior to wood chips or sawdust for building low-volume forest roads.

ROAD CONSTRUCTION

Several segments of forest roads were constructed either entirely, or in part, with chunkwood for demonstration purposes and to provide field research sites for evaluating road performance. In total, about 2.5 miles of forest roads were built involving chunkwood. This paper gives a general overview of the application of chunkwood to low-volume forest road building and highlights typical related field and laboratory research findings. A more detailed and extensive treatment of field and laboratory testing are covered in an unpublished report (Hodek and Shook 1988) and a Master's thesis (Shook 1988).

Site Descriptions

For this initial research and demonstration program using chunkwood as a low-volume roadbuilding material, four diverse, different sites in Wisconsin were chosen on the Chequamegon National Forest. A brief description of each site follows.

Forest Road (FR) 481 (Hayward Site)

This was a swamp crossing. The total length of the road was 0.67 miles. The project included an existing grade with an approximate 1,700-foot relocation, of which 600 feet was through the swamp. Soils were classified as loamy sand (LS) with the swamp being classed as Carbondale. The trees were predominantly aspen, black spruce, and lowland brush. There was a substantial depth of peat beneath the vegetative swamp mat. The maximum peat depth was about 18 feet, and it had a high moisture content and very low shearing strength.

FR 583 (Medford Site)

This was a poorly drained site with soils classified as silty loam (SiL) to sandy loam (SL). The total length of the project was 1.14 miles including a 3,000-foot section having assorted chunkwood test sections. The remainder was built of pit-run gravel. The timber stand was predominantly aspen and sugar maple with pockets of lowland brush and tamarack. The nature of the soils on this site makes it impossible to operate conventional logging equipment during the spring of the year and wet periods.

FR 691B (Washburn Site)

This involved 0.6 miles of new construction. The soil is classified as a medium to coarse sand often referred to as "sugar sand" because of the similarity to granulated sugar when dry. Due to the lack of cohesion and uniform particle size, these soils have very little capacity to support traffic when dry. The timber on this site was mostly jack pine with smaller amounts of aspen and scrub oak.

FR 325 (Glidden Site)

This was an existing grade with a total length of 0.11 miles that included a 300-foot-long section having a series of mud holes with free-standing water. The soils ranged from loamy sand (LS) to sandy loam/loamy sand (SL/LS). The timber stand included black spruce, swamp hardwoods, spruce hardwoods, spruce-fir, and northern hardwoods.

Design Descriptions

The following are very generalized descriptions of the various test forest roads that were constructed. Schematic illustrations of each cross section used are included for detailed reference (fig. 1).

FR 481

This road included three test sections involving chunkwood. Two sections were across the swamp (fig. 2). The first 250 feet across the

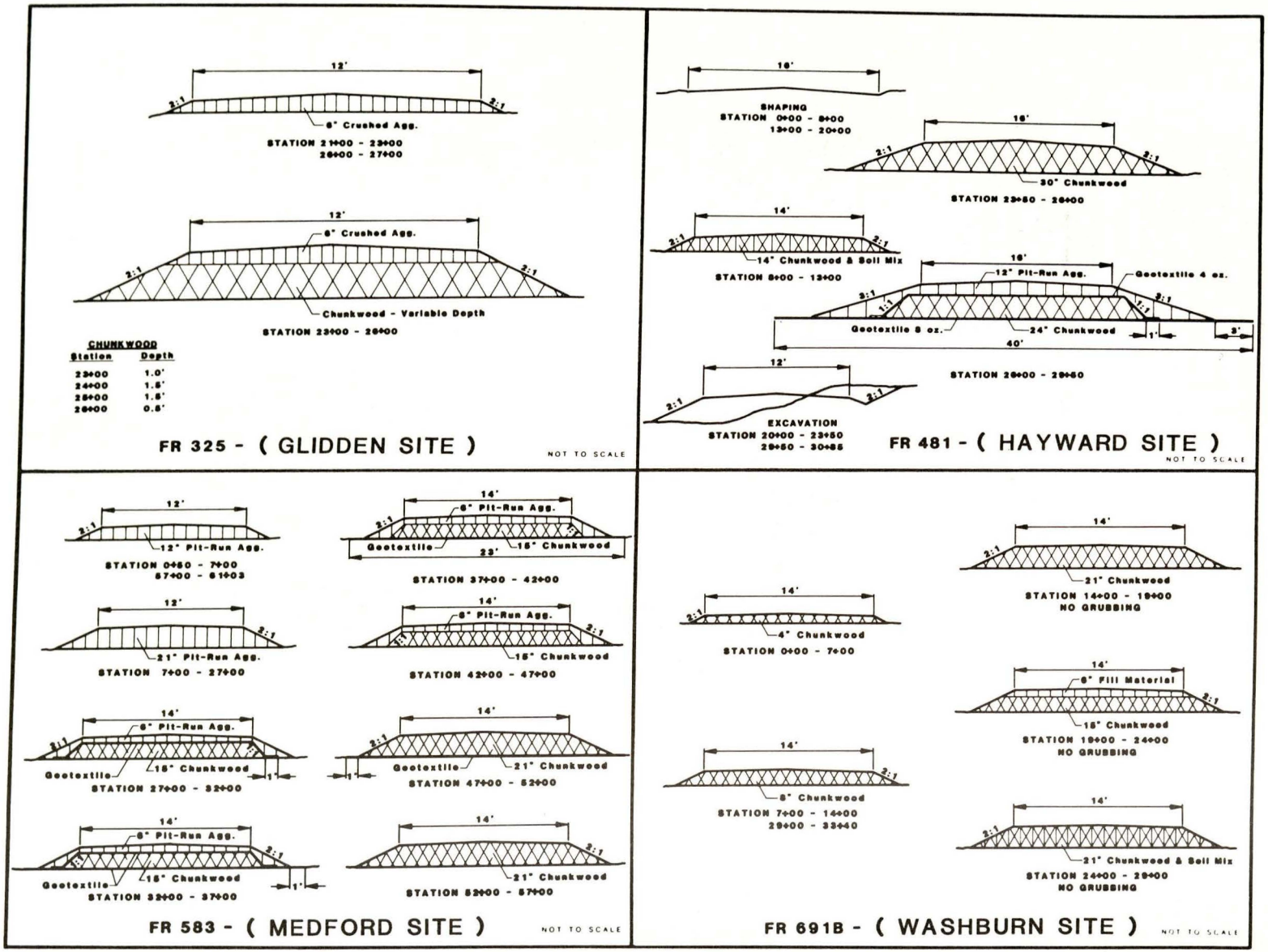


Figure 1.—*Typical cross sections of chunkwood test demonstration roads.*

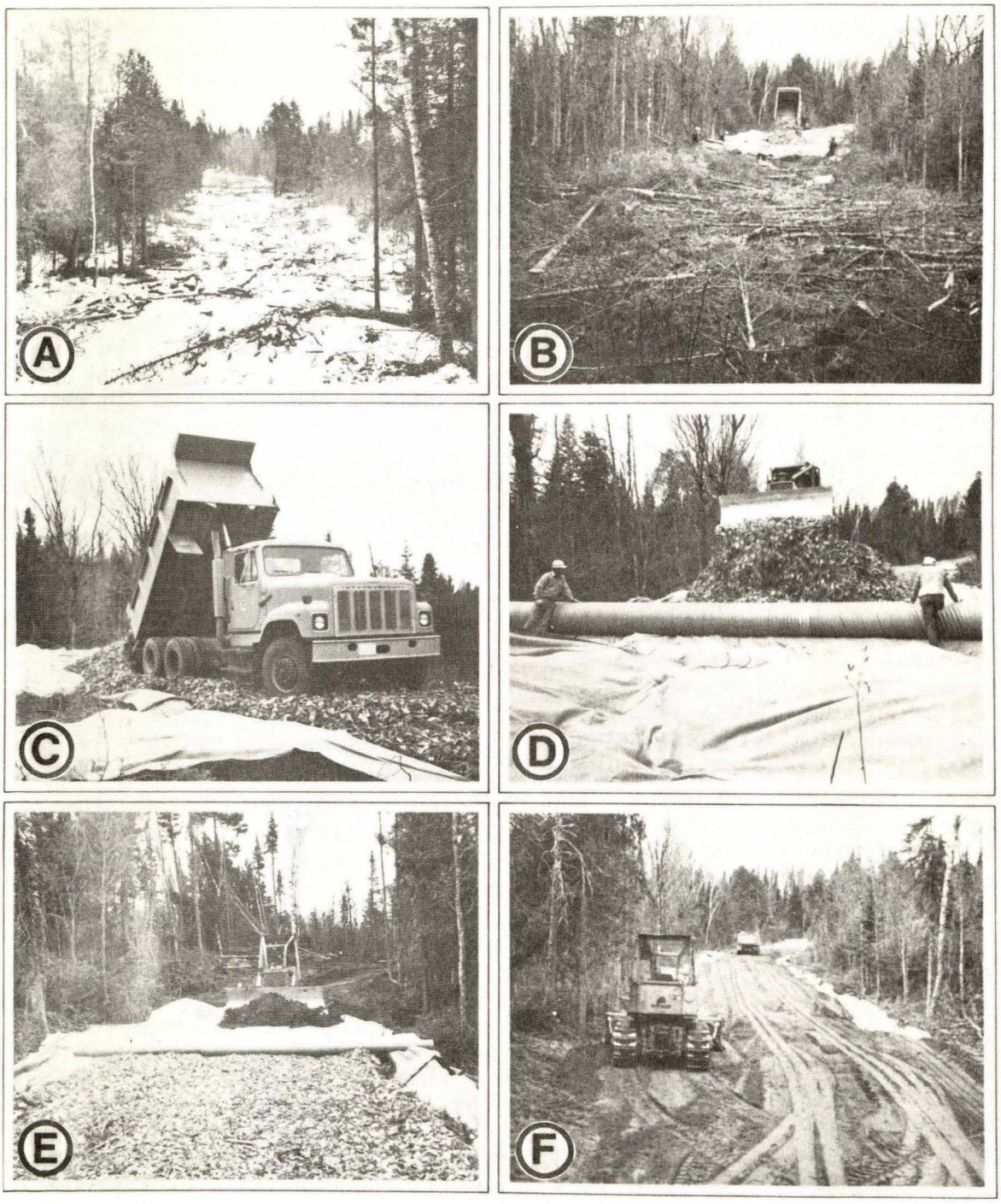


Figure 2.—*Swamp crossing at FR 481 (Hayward site): A. Right-of-way clearing; B. Ungrubbed swamp in foreground; C. Dumping of chunkwood onto geotextile fabric; D. Installation of culvert; E. Application of geotextile fabric and gravel over chunkwood base; F. Nearing completion of swamp crossing.*

swamp, where the peat was the shallowest, had 30 inches of chunkwood placed directly on top of the vegetative mat. The remaining 350 feet called for the placement of an 8-ounce geotextile fabric on top of the ungrubbed swamp. This was followed by 24 inches of chunkwood. A 4-ounce geotextile fabric was then placed over the chunks, and a minimum depth of 12 inches of pit-run gravel was placed on top of the fabric as the surfacing course. The principal purpose of the bottom fabric was as a separator to prevent the chunks from being lost into the vegetative mat and underlying peat. Load support was considered to be a minor function of the fabric. The function of the upper fabric was solely as a separator to prevent eventual mixing of the surface gravel with the underlying chunkwood over time. With this design, the chunkwood was, in effect, completely enveloped by fabric. During construction, there was no intentional compaction of the chunkwood other than that which was caused by the dump trucks and the bulldozer used to construct the road.

The third test section was built on loamy sand. Here the chunks were mixed with the soil. Our idealized goal was to produce an approximate 50/50 mix, but this was an impossibility without specialized mixing equipment. The mixing was done in-place with a front-end loader. Some sections received very lean amounts and others very heavy amounts of chunkwood in the mix. Prior to being tested, a portion of this section was compacted with a vibratory roller compactor weighing about 5,000 pounds.

FR 583

This test road was laid out to include six different design sections involving chunkwood. In simplest terms, the sections included only chunkwood, chunkwood on geotextile fabric with and without surfacing aggregate, chunkwood completely enveloped in fabric followed by surfacing aggregate, fabric used only to separate the surfacing aggregate from the underlying chunkwood, and surfacing aggregate placed directly on top of the chunkwood. These road sections were not compacted prior to being tested. Immediately after the chunks were produced, they were loaded into dump trucks and spread on the roadway. Only the 4-ounce geotextile fabric was used on this road.

FR 691B

The road built on sugar sand had five different design sections. Three sections received 4, 8, and 21 inches of chunkwood only. For the latter, no grubbing was done. A fourth section received a surfacing course of at least 6 inches of sugar sand placed on top of a 15-inch chunkwood base. There was no grubbing. In the fifth section, the sugar sand was mixed with the chunkwood in a targeted 50/50 mix. The road was 21 inches deep with no grubbing done. Mixing at this site was achieved by trickling sand onto the conveyor carrying chunks to a dump truck. Although this technique was much better than mixing on the ground with a front-end loader, it still resulted in considerable variation in the mix consistency. No fabric was used on this road. Compaction with a vibratory roller compactor was done on portions of several test sections.

FR 325

This road was constructed solely to demonstrate whether chunkwood could be used to fill in large mudholes within an existing roadway. Chunks were hauled to the site from a stockpile, dumped onto the roadway, and bulldozed until a roadbed surface was established well above the level of the standing water. Surfacing aggregate was then placed over the chunkwood base. Although this road received some traffic, no research testing was done.

Geotextile Fabric

The use of either woven or nonwoven geotextile fabric to strengthen forest roads is not new. It has been used by the logging industry for at least a decade. The Forest Service makes frequent use of geotextile fabric in its roadbuilding program. It was also used in this work as a separator and to add strength to chunkwood roads.

The geotextile fabric used was Supac N[3], which is a nonwoven fabric. Two different weights were used: a 4-ounce/square yard and an 8-ounce/square yard. Where greater strength and puncture resistance were needed such as when placed directly on a swamp mat, the 8-ounce fabric was used. The 4-ounce fabric was used when its function was merely as a separator. Both fabrics readily transmit water.

Chunkwood Production

Two experimental prototype chunkers were used in this project. The principal chunker was the machine built by the Forest Service at its Missoula Technology and Development Center in Montana (fig. 3). This machine is generally referred to as the "Missoula chunker." The second machine, generally referred to as the "Houghton chunker," was the original experimental wood chunker built by the Forest Service at its Forest Engineering Project in Houghton, Michigan. Both machines employ the same method to sever wood chunks. The Missoula chunker, which is powered by a 300-horsepower engine, could chunk softwood trees up to 12 inches in diameter. The Houghton chunker had a maximum tree diameter capacity of 8 inches and was powered by a 175-horsepower engine with a slip clutch between the engine and the cutter disc. The clutch was adjusted to slip at about 100 horsepower.

Both wood chunkers were time-studied to determine their productivity, even though they are experimental prototypes. The reader is therefore cautioned not to consider the reported productivity of these prototype machines as that of a commercial wood chunker. Further, the operators of both chunkers had no prior experience operating similar equipment such as whole-tree chippers. Inexperienced operators would obviously not attain as high a productivity level as would skilled operators.

---

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture or Michigan Technological University to the exclusion of others that may be suitable.*

Figure 3.—*USDA Forest Service, Missoula Technology and Development Center precommercial prototype wood chunker.*

The Missoula chunker was studied at three forest road sites (FR's 481, 583, and 691B) and the Houghton chunker at only one site (FR 583) (fig. 4). The first site where chunkwood was produced was FR 481. This was mostly a learning experience for the operator. Here the mean productivity, based on 16 observations over 2 days, was slightly under 15 green tons per productive hour. A single observation was a nominal 20-cubic yard dump truckload. The actual weight of chunks in each truckload was determined by using portable platform scales.

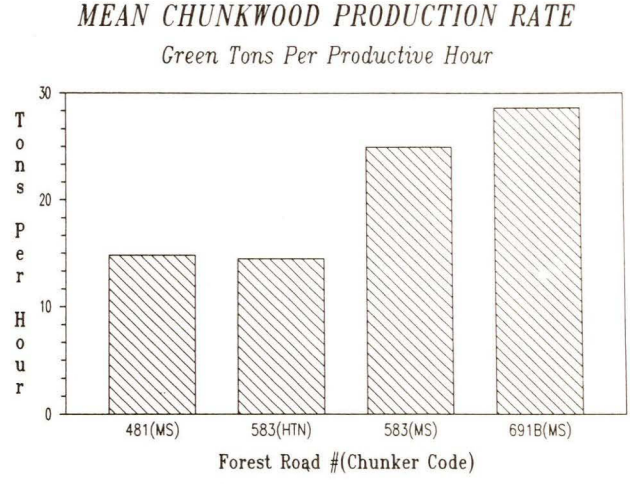


Figure 4.—*Mean chunkwood production rates. (MS and HTN indicate the Forest Service Missoula and Houghton prototype chunkwood machines.)*

After this initial learning period with the Missoula chunker, there was a dramatic increase in productivity. For FR's 583 and 691B, the respective mean production rate was about 25 and 29 green tons per productive hour. Differences in productivity can be partially attributed to physical differences between the trees at each of the sites such as tree diameter and quantity and size of limbs. There was also no question that the operator's learning curve affected the results. The mean weight of chunks in a truckload also varied. For FR 481, the mean truckload weight was about 9,500 pounds, whereas it was closer to 10,800 pounds for the other two roads. Larger capacity trucks, had they been available, would have been preferred.

ROAD CONSTRUCTION COSTS

Records were kept of the various construction elements for each of the forest roads. Although building roads with chunkwood is itself unique, the key unique element is the production of the roadbuilding material with a wood chunking machine. The primary objective of this work was to test and evaluate the suitability of chunkwood for building forest roads. The objective was not to demonstrate the reliability of wood chunking machines. Because the two chunkers used in this project were strictly experimental prototypes, there were several chunker breakdowns that would not be characteristic of a commercially manufactured machine that is the result of extensive design and development. The actual road construction costs from this work were heavily biased to the high side due to operational delays caused by chunker downtime and repair costs. Because of the unusual conditions associated with this initial chunkwood roadbuilding effort and this high-side cost bias, the actual costs for each test road are not reported here. However, they are available upon request from the Forest Engineer located at the Chequamegon National Forest in Park Falls, Wisconsin.

The actual cost records, along with assumptions made regarding chunker availability and productivity, were used to project unit costs for chunkwood road construction that would be more useful for making first-order estimates of future road construction costs (table 1). This information was then used to generate estimated per-mile costs for constructing chunkwood roads similar to the different test design sections (table 2). The reported costs in the preceding tables are based on using a 20-cubic yard capacity truck. If a truck with greater capacity can be used, costs would be lowered. More reliable construction cost data will become available as techniques and equipment for chunkwood road building become more refined.

FIELD EVALUATION

After construction of all test segments of chunkwood roads, Forest Service tandem-axle dump trucks loaded with sand were driven on these test roads to simulate the hauling activities associated with normal logging operations. Gross vehicle weight was approximately 50,000 pounds, with rear axle loads of about 20,000 pounds each. Although the loaded dump trucks were well under the gross loaded weight of many logging trucks, they were used in this initial study because they were owned and under the complete control of the Forest Service. What is of prime importance is the axle loading and not the gross loaded vehicle weight. The 20,000-pound axle load with the dump truck was as severe, if not more so, than those resulting with loaded logging trucks. Roadway performance was evaluated by measuring road rutting, roadway lateral shoving, and roadway stiffness at FR's 481, 583, and 691B. Also, general settlement was determined at the FR 481 swamp crossing.

Road rutting due to truck traffic was measured with a transverse profilometer board (fig. 5). Based upon the observations at 50 profile stations at the three field sites, a modest net loss of volume was observed. The loss was attributed to a combination of particle degradation and chunkwood compaction due to traffic. Based on profile measurements on FR 691B after 102 and 200 truck passes, there was no significant additional loss in volume after the first 100 passes.

Plate load tests were conducted to determine the relative stiffnesses of various roadway sections.

Table 1.—*Projected chunkwood road construction costs under near optimum conditions (CY = cubic yards and SY = square yards)*

DAILY OPERATING COST W/OPERATOR (prorated according to estimated hours of use):

Feller/buncher	$ 400
Skidder	320
Chunker	480
Trucks (two)	400
Bulldozer	280
	$1,880/day (Applies to chunkwood only.)

ASSUMPTIONS:

Work day	8 hours
Truck capacity	20 CY
Weight/20 CY truckload	5.4 tons
Chunker productivity	See below

COST OF CHUNKWOOD (produced in-place):

Production rate (green tons/hour)	Truckloads/day	CY/day	$/CY
25	37	740	2.54
26.8 (mean - FR 691B)	40	800	2.35
30	44	880	2.14

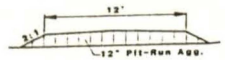
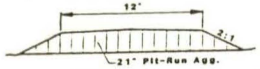
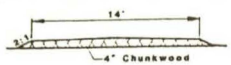
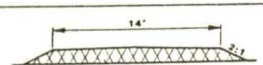
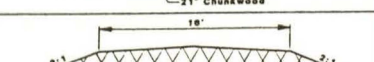
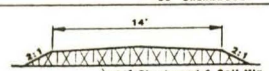
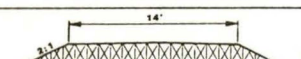
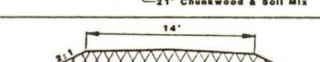
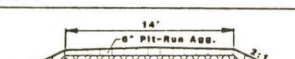
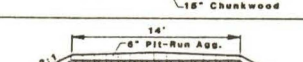
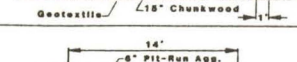
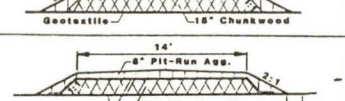
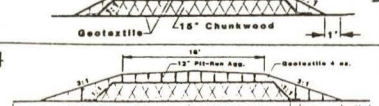
APPROXIMATE COST OF CONVENTIONAL SURFACING MATERIALS:

Process		
Pit-run aggregate	-	
Crushed aggregate	**$ 2.50/CY**	
Load and haul		
Haul distance	5 miles	35 miles
Pit-run aggregate	**$ 2.50/CY**	**$ 6.30/CY**
Crushed aggregate	**$ 2.50/CY**	**$ 6.30/CY**
Placement		
Pit-run aggregate	**$ 0.70/CY**	
Crushed aggregate	**$ 0.50/CY**	

GEOTEXTILE FABRIC:

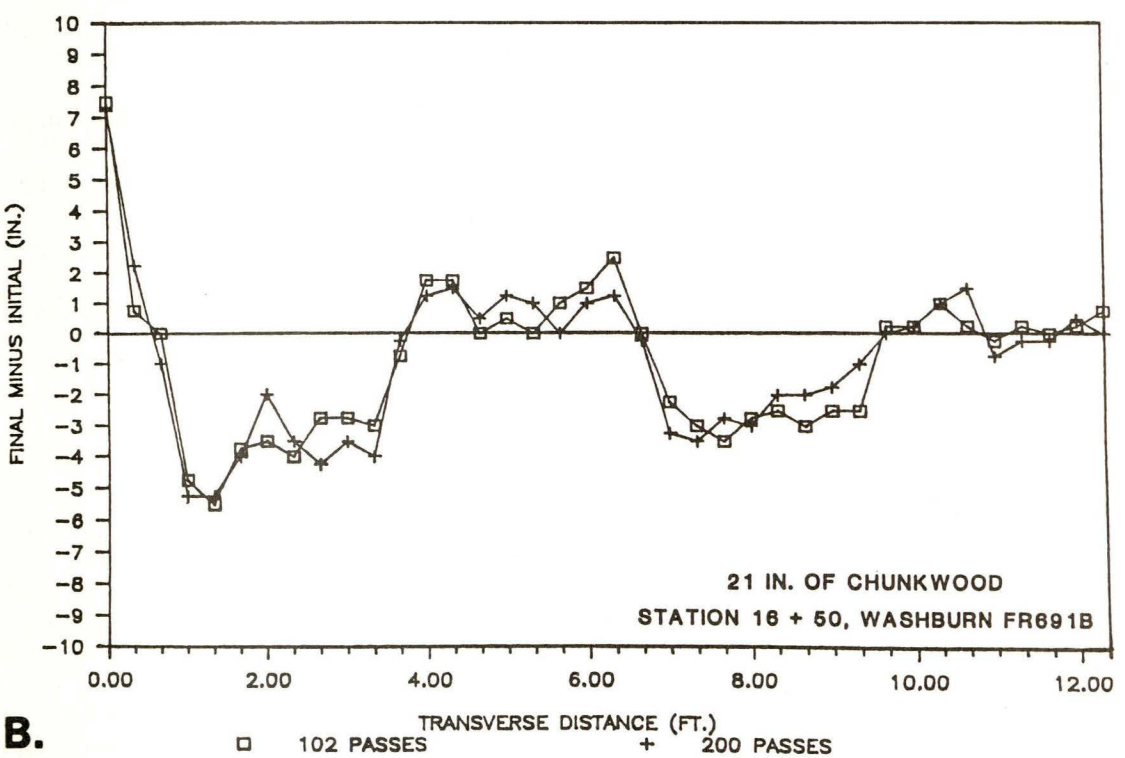
	8-ounce	4-ounce
Unit cost	**$ 0.88/SY**	**$ 0.45/SY**
Placement	**$ 0.12/SY**	**$ 0.05/SY**

Table 2. Estimated material requirements and construction costs for different road sections.

ROAD SECTIONS	CUBIC YARDS/MILE		SQUARE YARDS/MILE		ESTIMATED IN-PLACE COSTS/MILE			
	Chunkwood	Pit-run Agg	Geotextile 8 oz.	Geotextile 4 oz.	Chunkwood $	Pit-run Agg $	Geotextile $	TOTAL $
1 	NA	2740	NA	NA	NA	8800	NA	8800
2 	NA	5300	NA	NA	NA	17,000	NA	17,000
3 	955	NA	NA	NA	2200	NA	NA	2200
4 	2000	NA	NA	NA	4700	NA	NA	4700
5	5990	NA	NA	NA	14,100	NA	NA	14,100
6 	10,270	NA	NA	NA	24,100	NA	NA	24,100
7 	2980	745	NA	NA	7000	2400	NA	9400
8 	4790	1200	NA	NA	11,300	3800	NA	15,100
9 	5990	NA	14,500 NA	NA 14,500	14,100 14,100	NA NA	14,500 7200	28,600 21,300
10 	3730	2260	NA	NA	8800	7200	NA	16,000
11 	3730	2260	NA	13,200	8800	7200	6600	22,600
12 	3730	2260	NA	13,500	8800	7200	6800	22,800
13 	3730	2260	NA	26,700	8800	7200	13,400	29,400
14 	7820	6845	23,470	16,840	18,400	21,900	31,900	72,200

NA = Not Applicable

A.



B.

Figure 5.—*Measurement of road rutting caused by test vehicle. A. Transverse profilometer board used to measure transverse road profile. B. Typical graphic representation of rutting in a roadbed profile.*

A 12- or 18-inch-diameter plate was jacked into the roadbed using a 60-ton hydraulic jack with the Forest Service truck as the reaction. Plate load test results from the Washburn (FR 691B) and Hayward (FR 481) sites proved inconclusive. Results from the Medford (FR 583) site indicated that road sections constructed of gravel/geotextile/chunks were stiffer than sections of chunkwood/gravel, chunkwood/geotextile, or chunkwood alone (fig. 6). Although the stiffness of the roadway sections varied, none of the tests that were conducted revealed classical load-bearing capacity failure. This was likely due either to the limited reaction provided by the loaded dump truck or the short stroke of the jack cylinder.

Lateral movement of road material was determined by setting with a transit a single line of offset stakes at 50-foot intervals placed just beyond the truck-tire wheel ruts. Before-and-after traffic stake location readings were taken. The relative lateral movement was determined by the difference between these two measurements.

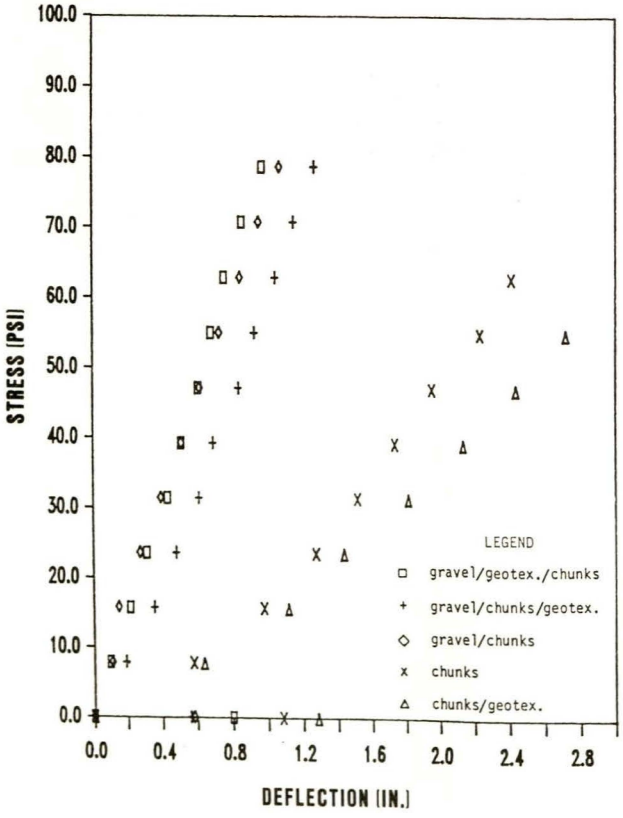


Figure 6.—*Plate load test results for FR 583 (Medford) after 105 test truck passes over various chunkwood road test sections.*

Results from the three sites showed insignificant lateral movement due to truck traffic.

LABORATORY STUDIES

The laboratory testing program was designed to investigate selected mechanical properties of chunkwood related to highway design parameters. First-generation procedures were designed to evaluate chunkwood's compactability, compressibility, and water permeability properties. The design of these procedures was based primarily on known and accepted methods developed for inorganic soils and rock fills with modifications to accommodate chunkwood's unique characteristics. Chunkwood from each of the three test sites was evaluated.

Compaction and compression of the chunkwood were achieved by using a servo-hydraulic loading system capable of applying a cyclic load to the sample through the selection of various available loading functions. A sample mold was constructed based on considerations of chunkwood particle size and the loading capacity of the servo-hydraulic system. The sample mold was a cylindrical steel tank 3 feet high and 3 feet in diameter (volume = 21 cubic feet). The same mold also served as a permeameter.

For the compaction tests, bulk chunkwood samples were compacted in three successive approximate 1-foot layers in the mold. Compaction was achieved by applying a full coverage cyclic load of about 10,000 pounds at a frequency of 1 cycle/second (cps) for 50 cycles (fig. 7). This is defined as slow-cyclic compaction.

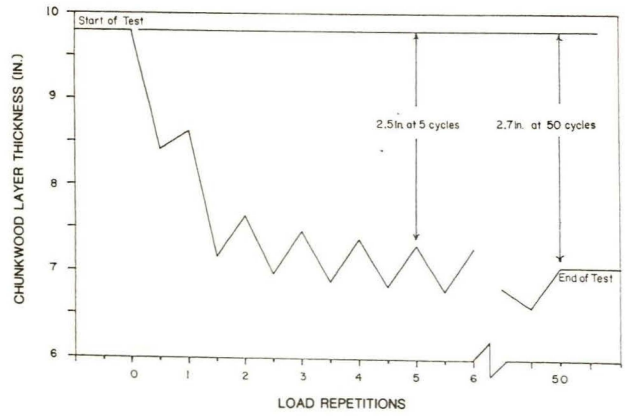


Figure 7.—*Typical laboratory compaction record illustrating the characteristic behavior of confined chunkwood to repeated loadings.*

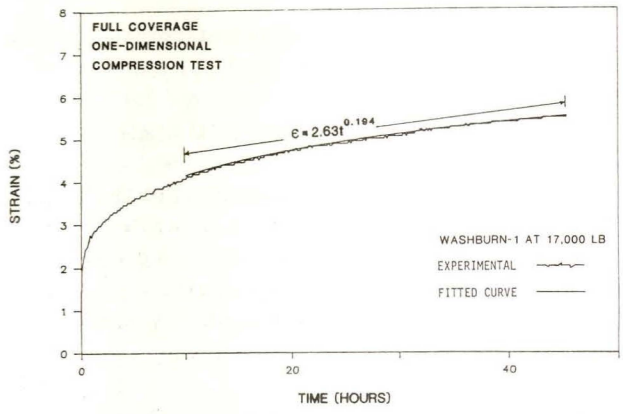


Figure 8.—*Compressibility of chunkwood as illustrated by a typical full coverage, one-dimensional compression test result.*

After completing the slow-cyclic compaction tests, full coverage, one-dimensional compression tests were conducted on the chunkwood samples by applying a constant load for periods of 24 to 48 hours, and the strain was monitored (fig. 8). One-dimensional compression tests at differing stress levels on the same sample showed that the chunkwood behaves similarly to a mineral soil. That is, its compressibility increases when the stress level exceeds the maximum previous stress level.

Plate load tests were conducted by pushing an 8-inch-diameter plate into the compacted/compressed chunkwood sample at a constant rate of penetration of 0.5 inch/second. From plots of stress versus displacement, a relative stiffness index for each sample was determined by calculating the slope of the straight line portion of each plot (fig. 9). Relative stiffness index values nominally ranged between 35 and 55 pounds/cubic inch.

The constant-head permeability method was used to determine the coefficient of permeability for chunkwood. The head loss across the sample was measured at a constant flow rate. Darcy's standard engineering equation for laminar flow was used to calculate the coefficient of permeability for a given flow rate.

Permeability tests conducted on the chunkwood samples yielded average coefficients of permeability ranging from about 19 feet per minute (fpm) to 117 fpm. This range is extremely high compared to typical values of 5×10^{-3} fpm and 5×10^{-5} fpm for clean gravels and uniform coarse sand, respectively. With such high permeability, it is conceivable that low-volume roads constructed with chunkwood may not need culverts to allow the flow of water beneath the roads in low-lying or swampy areas.

It has not been established whether field construction of chunkwood roads can achieve the same void ratios used for the laboratory coefficient of permeability determinations. If not, the as-built coefficients of permeability will be even higher than those reported here.

SUMMARY AND CONCLUSIONS

Numerous test sections of low-volume forest access roads were built with chunkwood over a

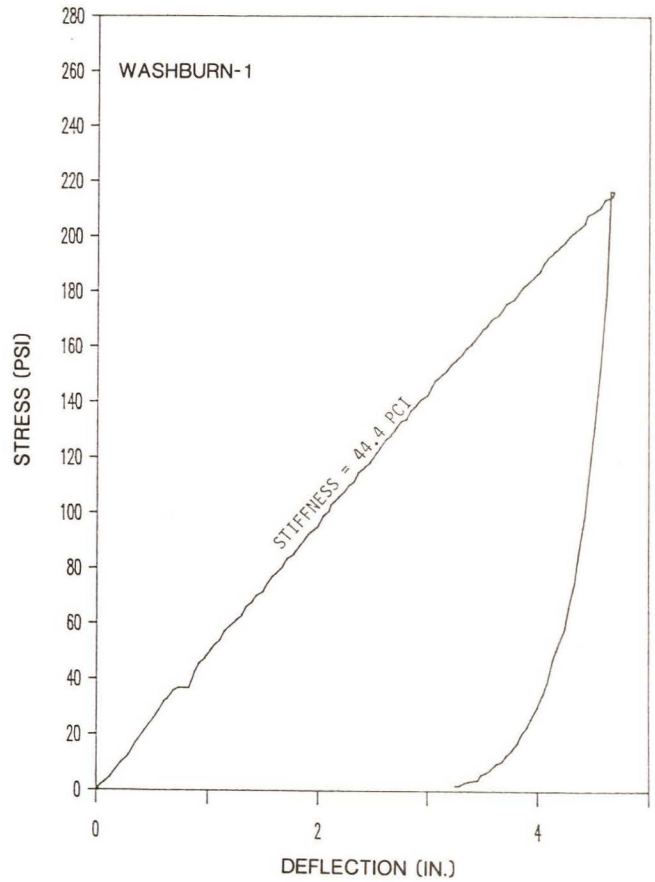


Figure 9.—*Chunkwood stiffness index as illustrated by a typical plate load stress/displacement plot.*

swamp, in "sugar sand," and on top of silty clay with the water table near the ground surface. All road test sections were then subjected to repeated truck traffic to evaluate roadway performance. Additionally, laboratory studies of chunkwood were undertaken to develop an understanding of some important mass properties relative to its use as a roadbuilding material.

The analysis of the field performance measurements of the chunkwood road sections as well as the test vehicle driver opinions shows that chunkwood can be a viable material for use as a surfacing material and a lightweight structural fill for low-volume forest roads.

The chunkwood did not show unacceptable compaction or material loss due to traffic. Lateral stability of chunkwood fills was exceptionally good. Surface rutting caused by traffic channelization was easily and quickly corrected by motor grading, and rutting did not develop when vehicles were allowed to off-track the previously traveled path.

The use of a geotextile fabric acts as a reinforcement and can measurably increase the section's stiffness as shown by the plate-loading tests when the geotextile is appropriately located in the cross section. It was also an effective separator to prevent the loss of surfacing aggregate into the voids in the chunkwood lift and the loss of some chunkwood particles into an underlying swamp mat.

As little as 4 inches of chunkwood placed directly on top of "sugar sand" effectively improved the stability of the road and, as an added benefit, significantly reduced the dusting problem. A deeper surfacing course of chunkwood all but eliminated dusting.

The performance of a chunkwood/soil mixture was inconclusive. This was due to a heavy rainfall just prior to testing and the inconsistent blending of the mix.

Laboratory testing was very successful, and some important characteristics of chunkwood were determined. These characteristics relate to the coefficient of permeability and stress-history.

The coefficient of permeability determinations for chunkwood gave values several orders of magnitude greater than would be expected for typical sand or gravel soils. It is expected that the as-built coefficient of permeability in the field will be at least as great as that determined in the laboratory. This is a very desirable characteristic because it favors both vertical and lateral drainage, and suggests an additional use of chunkwood to mitigate seepage and stability problems.

It was found that the moisture content of chunkwood has a measurable effect on creep, stiffness, and compaction. As the moisture increased, creep increased, stiffness decreased, and compaction increased. It is felt that the effects are due in part to the fact that wood strength varies inversely with its moisture content (fig. 10).

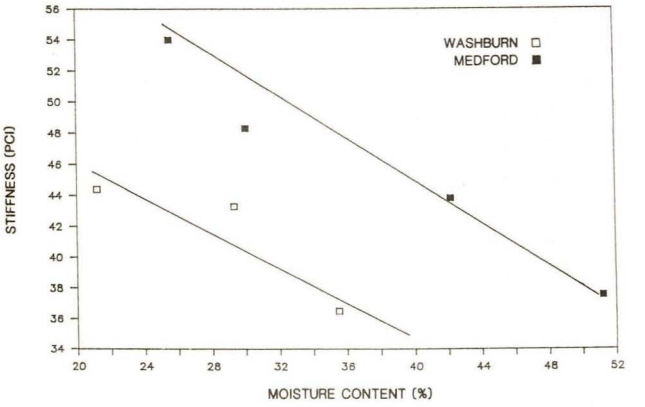


Figure 10.—*Relationship between chunkwood sample stiffness and moisture content. WAS = Washburn site (sugar sand) and MED = Medford site (wet, silty clay).*

PRELIMINARY RECOMMENDATIONS

This initial trial has successfully introduced the concept of chunkwood roads and has demonstrated that chunkwood is a viable alternative roadbuilding material. Availability, bottom-line economics, or some other engineering justification will ultimately influence the choice of materials—whether it be chunkwood or conventional roadbuilding gravel.

Many questions pertaining to roadbed design and material characteristics must be answered before we can truly understand and predict chunkwood road performance. However, based on the performance of these trial chunkwood roads and subjective observations, some preliminary recommendations can be made regarding the use of chunkwood in several kinds of forest roadbuilding applications. As more is learned about the performance and optimum design of chunk-wood roads built over swamps, on uniformly-graded sugar sand, or on wet, fine-grained soils, the recommendations that follow can be refined and expanded.

Sugar sand can be stabilized by applying a relatively shallow (4- to 8-inch) surfacing course of chunkwood. Besides stabilizing the sand, it reduces severe dusting from traffic.

Another alternative to stabilizing uniform sand is to use chunkwood as an admixture. A high proportion of chunkwood to sand is recommended. Although we have no supporting data, an 80/20 mix by volume is initially suggested. Ideally, the best performance should result when the chunkwood particles are in intimate contact with each other, and the sand fills the interparticle voids.

Swamp or muskeg crossings stand out as an excellent application for lightweight chunkwood fills. In such an application, it is recommended that trees and slash from the right-of-way clearing that are not recovered for chunking be concentrated in the area of the intended forest road. Unless the road is to have an extremely short life, it is also recommended that an 8-ounce geotextile fabric be placed over the concentrated slash before applying the chunkwood. The combination of fabric and slash will strengthen the swamp mat, and the fabric will prevent the loss of chunkwood particles to the underlying peat through natural holes in the vegetative mat. Without the fabric separator, the chunks inevitably will be pumped through these holes under the load of traffic.

In a swamp crossing application, the load-supporting capability of the road is critical and is directly related to the overall depth of the road. A chunkwood lift of at least 30 inches is recommended if the entire road is to be built only of chunkwood. Chunkwood roads can be readily reshaped and more chunkwood added as needed from a nearby stockpile. Where the chunkwood is to be enveloped in geotextile fabric and covered with a gravel aggregate surfacing course, a minimum chunkwood depth of at least 24 inches is initially recommended for the swamp crossing application.

Though definitive data on life expectancy are not yet available, it is hypothesized that a road built only of chunkwood would likely have a shorter life than one where chunkwood is completely enveloped in geotextile fabric and then covered with a surfacing course of pit-run or crushed aggregate. Surface exposed chunkwood is likely to rot faster than that buried under saturated soil. This hypothesis is based on the soundness of logs that are still being uncovered in old corduroy roads that have been buried for many years. Frost heaving brings many of these buried logs to the ground surface. Also, it is known that wood left lying on the ground will rot much faster than wood that is buried in water-saturated soil. Future research should address techniques to extend the life of chunkwood. The use of additives, such as borate, may warrant exploration.

With fine-grained soils high in clay content and a water table near the surface, catastrophic road failure, as in a swamp crossing, is not the problem. The problem is to maintain a road that retains its trafficability and does not become a quagmire under extremely wet ground conditions. Chunkwood will not become a quagmire. The only recommendation here is that the bed of chunkwood be deep enough to keep the road surface sufficiently elevated. This would be true whether the road is made entirely of chunkwood, or if fabric and surfacing aggregate are used in combination with chunkwood.

Although preliminary in nature, this study demonstrates not only that chunkwood is effective in stabilizing unpaved roadways, but that chunkwood as a bulk material is amenable to the determination of engineering characteristics.

Once these behavioral characteristics are fully understood, rational roadway design procedures can be developed for chunkwood just as they have been for natural soil and rock.

CONVERSIONS

1 foot = 30.48 centimeters
1 inch = 2.54 centimeters
1 pound = 16 ounces = 0.4536 kilogram
1 ton (2,000 pounds) = 0.9072 tonne (907.194 kilograms)
1 cubic foot = 0.0283 cubic meter = 28.3206 liters
1 cubic yard = 0.7646 cubic meter
1 square yard = 0.8361 square meter
1 pound/cubic foot = 16.0184 kilograms/cubic meter
1 horsepower = 0.7457 kilowatt
Fahrenheit = 1.8 (Celsius) + 32

LITERATURE CITED

Arola, Rodger A. 1984. **Chunking of small trees - an alternative to chipping**. In: Robertson, Doris, proc. coord. Harvesting the South's small trees; 1983 April 18-20; Biloxi, MS. Proc. 7340. Madison, WI: Forest Products Research Society: 117-127.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A. 1985. **Chunking bundled small-diameter stems**. Forest Products Journal. 35(4): 40-42.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. **Involuted disc slicer**. U.S. patent 4,431,039. February 14. 11 p. Int. Cl.^{3} B27L 11/02. U.S. Cl. 144/176.

Bowman, John K.; Lidell, R. Brad; Schulze, Gary B. 1987. **The use of wood chips for low-volume road construction in the Lake States**. In: 4th International conference on low-volume roads; 1987 August 16-20; Ithaca, NY. Transport. Res. Rec. 1106. Washington, DC: National Research Council, Transportation Research Board: 1: 47-58.

Hodek, Ralph J.; Shook, Larry W. 1988. **Evaluation of chunkwood as a low-volume road building material. Draft final report**. U.S. Department of Agriculture, Forest Service, Chequamegon National Forest, Park Falls, WI, Contract 53-56A2-7-00015. Houghton, MI: Michigan Technological University. 62 p., appendices A-E.

Lidell, Richard B.; Bowman, John K. 1987. **The use of paper mill sludge to stabilize sand roads**. In: 4th International conference on low-volume roads; 1987 August 16-20; Ithaca, NY. Transport. Res. Rec. 1106. Washington, DC: National Research Council, Transportation Research Board: 1: 65-70.

Petersen, Dale R.; Zander, Almer D.; Swint, Ronald J.; Buss, Kenneth G.; Nichols, Roger A. 1981. **Slide area stabilization with sawdust and bark chips**. Transactions of the American Society of Agricultural Engineers. 24(4): 970-973, 976.

Shook, Larry W. 1988. **An investigation of selected geotechnical engineering properties of chunkwood**. Houghton, MI: Michigan Technological University. 77 p. M.S. thesis.

U.S. Chunkwood Machines[1]

Rodger A. Arola, Joseph B. Sturos, and Robert C. Radcliffe[2]

Abstract.—The USDA Forest Service has patented three wood chunking machines. This paper highlights the results of extensive research testing with a laboratory version of one of these machines, the involuted single-disc chunker. Tests were performed on individual logs from a number of common Lake States species and on bundled small-diameter stems. When the machine was outfitted with 1/4-inch-thick blades, the mean energy required at the cutter disc to produce 2- to 4-inch-long wood chunks ranged from 1.2 horsepower-minute/cubic feet (hp-min/cu ft) for the species with the lowest specific gravity to 2.5 hp-min/cu ft for that with the highest specific gravity. Specific gravity was significant at the 99-percent level on energy requirements. The energy to chunk aspen and red maple with 3/8-inch-thick blades increased 52 and 27 percent, respectively. Energy required to chunk frozen aspen and red maple was 64 and 24 percent more than that needed for unfrozen wood, respectively. Both specific gravity and log diameter were significant at the 99-percent level on power requirements. A family of linear regression lines was generated to predict power requirements for chunking several species of trees and a range of log diameters. For the species tested, chunkwood bulk density ranged from 20 to 25 pounds/cubic foot. When chunking bundled small-diameter stems, production rates ranged from 17 to 31 cu ft/min, power requirements from 15 to 23 hp, and energy from 3/4 to 1 hp-min/cu ft. The stem billets were uniform between 3-1/2 to 4 inches long. Field production studies were conducted with two precommercial demonstration prototypes. Mean production rate with the second-generation prototype in a jack pine whole-tree chunking system was 29 green tons per productive hour with trees up to 12 inches in diameter. With mixed hardwood trees 10 inches or less in diameter, mean production rate was 26 green tons per productive hour. Mean production rate with the 8-inch-diameter capacity prototype was 14 tons/hour in mixed hardwoods.

WOOD CHUNKING MACHINES

There are three principal objectives to this paper. The first objective is to cite the development of three wood chunking machines by USDA Forest Service researchers. The second is to present detailed information obtained from extensive laboratory testing of one of the wood chunking machines, the involuted single-disc chunker. The third is to present basic data on chunkwood production rates for two different-sized field demonstration prototypes.

The concept of chunking and chunkwood was first introduced by Forest Service researchers in

[1]*Paper presented at the International Energy Agency/ Bioenergy Conference, Task III/Activity 6 and 7 "Production, storage, and utilization of wood fuels." [The Swedish University of Agricultural Sciences, Uppsala, Sweden, December 6-7, 1988.]*

[2]*Rodger A. Arola, Joseph B. Sturos, and Robert C. Radcliffe are Research Mechanical Engineer, Mechanical Engineering Technician, and Electronic Technician, respectively, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

the mid-1970's. The development of the original chunking machine was prompted by the initiation of a national program of research within the Forest Service to improve forest utilization. A major thrust of the national program was to recover underutilized small trees and forest residues as raw material to manufacture structural-grade exterior flakeboard (U.S. Department of Agriculture, Forest Service 1978).

The basic purpose of the chunker was to reduce small trees and residues into elongated particles termed "fingerlings." The fingerlings were to later be reduced into long, paper-thin flakes by a ring flaker. The flakes were then combined with an appropriate resin, and the mixture was pressed into flakeboard. The proposed ideal-sized fingerling was from 2-1/2 to 3 inches long in the fiber direction and about 1 inch in cross section. The size was proposed on the basis of the operating characteristics of a ring flaker and required particle orientation with respect to the flaking knives.

Because no commercial machine was capable of reducing trees and residues into the desired fingerling particles, Forest Service research engineers in Houghton, Michigan, developed the first wood chunker. This patented device employed a spiral cutter blade mounted on a rotating shaft and was called a spiral-head (or helical-head) chipper (Barwise *et al.* 1977). Laboratory research trials conducted with an experimental machine established power and energy requirements, general machine performance, and flakeboard properties made from fingerling-derived flakes (Erickson 1976, Gardner *et al.* 1978, Haataja *et al.* [1984]). A field version of this machine was later fabricated for research and demonstration purposes (Arola and Sturos 1982).

About the same period that the spiral-head chipper (chunker) was developed in the United States, a nearly identical machine was developed in Finland (Hakkila and Kalaja 1981). Commercial models of the Finnish machine have been sold principally in Scandinavia and Europe, initially under the trade name Kopo and currently under the name Sasmo[3]. The Finnish conescrew chipper/chunker has been tested extensively (Hakkila and Kalaja 1981, Nurmi 1986) and is the subject of a separate paper at this conference by Nurmi. For these reasons, we will not discuss the laboratory version of the United States spiral-head chunking machine in this paper because it would be redundant and confusing.

It quickly became obvious that the larger than pulp chip-size particles produced by the spiral-head chipper had an immediate potential application as an alternative form of biomass fuel. Pursuant to developing a more productive field machine than the spiral-head chipper to comminute small trees into larger fuel particles, a second chunking machine evolved from Forest Service researchers in Houghton (Barwise *et al.* 1984). One configuration of this U.S. patented machine has been referred to as an involuted single-disc wood chunker. However, the patent also describes a machine configuration with two opposing but matching discs mounted either horizontally or vertically.

Initially, laboratory prototypes of both the single- and double-disc chunkers were fabricated and tested. The single-disc version was later extensively tested (Arola *et al.* 1982, 1983a, 1983b, 1985). Once proven in the laboratory as an aggressive wood chunking machine, a field prototype of the single-disc chunker was developed at the Forest Service Houghton laboratory—this machine is generally referred to as the "Houghton chunker." Subsequently, a second-generation, precommercial, demonstration prototype single-disc chunker was built at the Forest Service Technology and Development Center in Missoula, Montana—this machine is commonly referred to as the "Missoula chunker." The purpose of both machines was to enable expanded research with chunkwood and to enhance technology transfer by conducting potential user group and public demonstrations of wood chunking.

---

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others that may be suitable.*

A third Forest Service wood chunking machine was developed recently at Houghton. Patented as the Multi-Product Wood Processor (Kangas *et al.* 1986), a laboratory prototype was research tested for performance; the results are summarized in a separate paper that is published in the proceedings of this conference (Sturos 1989). The results of trials with this laboratory machine, referred to as the "teardrop chunker" because of the shape of the cutter opening, will not be duplicated in this paper.

INVOLUTED SINGLE-DISC CHUNKER

A special word of caution is appropriate before discussing power and energy required for chunking with the involuted single-disc chunker. It is extremely important for the reader to understand that the power and energy determinations were made as close to the actual cutter blades as possible (i.e., at the cutter disc shaft) and should not be interpreted as being representative of the gross requirements for a field wood chunking machine.

Machine Description

The laboratory version of this wood chunker was designed to reduce roundwood bolts less than 9 inches in diameter into chunks ranging from cigarette package-size to entire 2- to 4-inch-long discs equal to the diameter of the material chunked (figs. 1 and 2). The flywheel and carrier for the cutting blades is a 1-3/4-inch-thick, 3-foot-diameter steel disc. The disc is mounted on a horizontal shaft running in a pair of bearings secured to a rigid frame (fig. 3). Three curved, 24-inch-long, detachable, triangular blades, bent on an 18-inch radius, are mounted 120 degrees apart and positioned on the face of the disc so that their curved plane is perpendicular to the face of the disc and at right angles to the axis of the workpiece. The leading edge of each blade is set at a greater radial distance from the center of shafting than the trailing edge. This blade mounting arrangement gave a self-feeding action although feed rolls still are required.

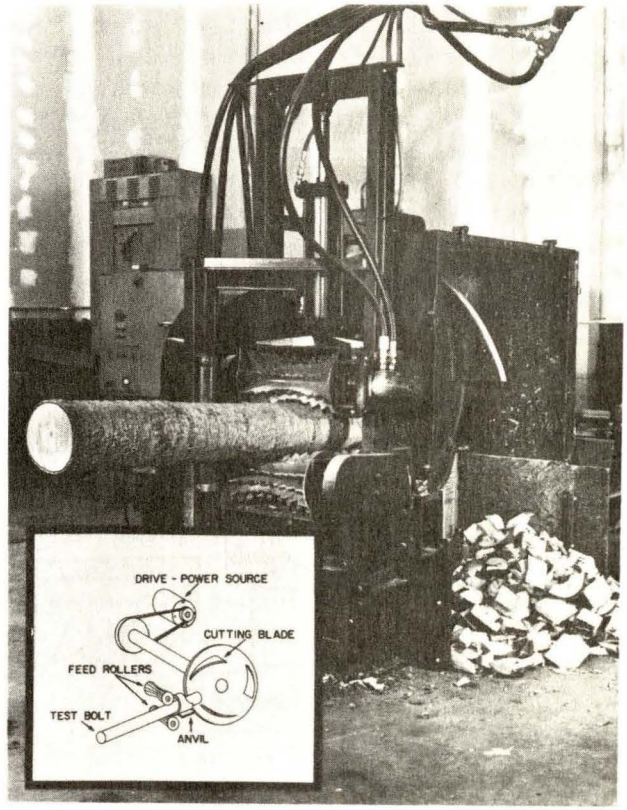


Figure 1.—*Experimental involuted single-disc wood chunker with simplified schematic insert.*

Figure 2.—*Chunkwood produced by the experimental involuted single-disc chunker.*

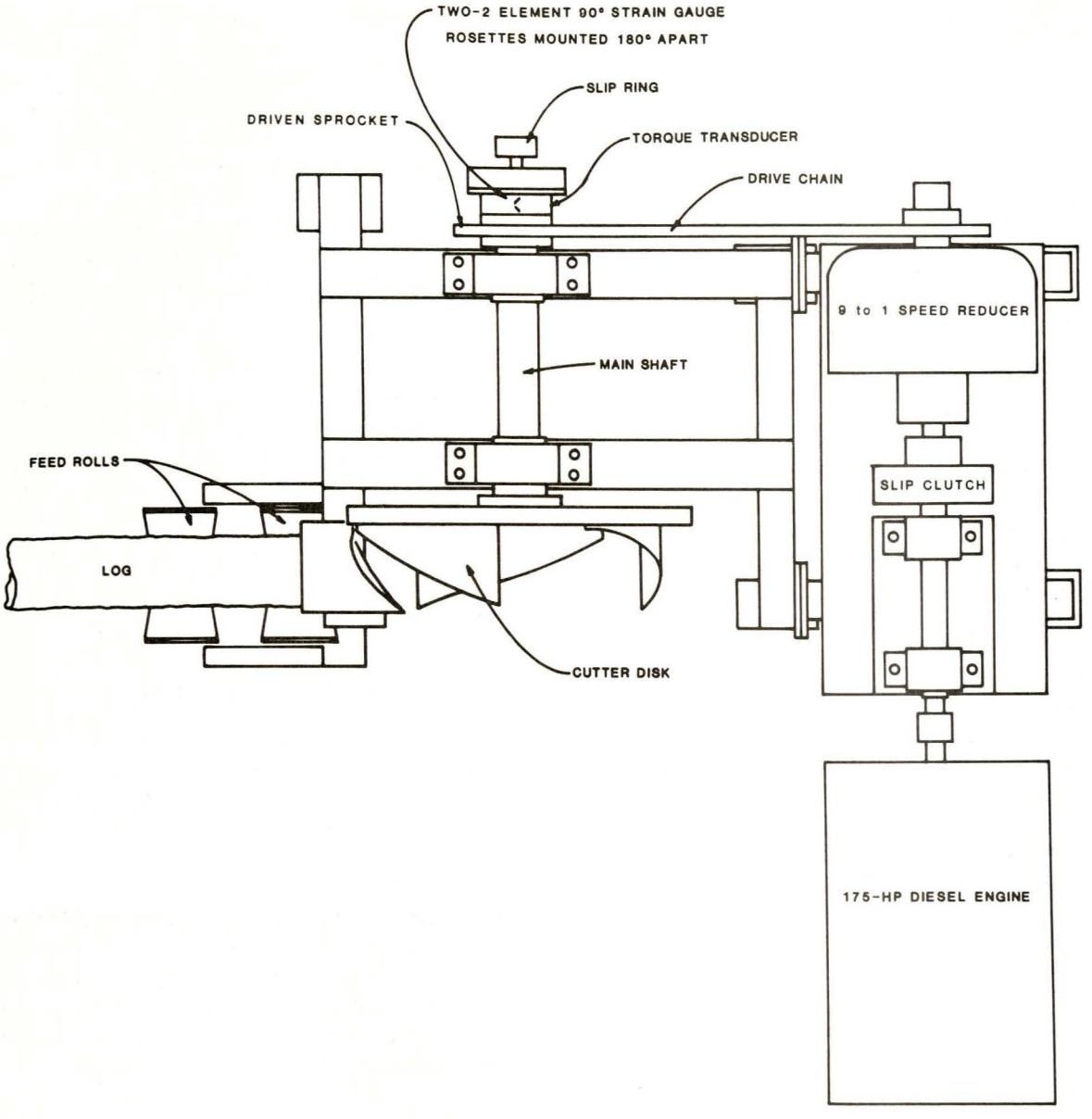


Figure 3.—*Schematic of experimental wood chunker and drive system.*

The workpiece (log or whole tree) is fed through a tubular anvil made from a 9-1/2-inch-diameter pipe horizontally secured to the infeed frame. The anvil tube is located near the rim of the disc but offset from the plane of the disc so the material being chunked matches the cutting blades. The center of the anvil tube is positioned slightly below the disc center to obtain the desired entry and exit of the blades from the log (or tree). The anvil tube is contoured to provide a slight clearance between it and the rotating blades as the chunks are severed from the workpiece. A pair of powered feed rollers is positioned immediately ahead of the anvil. The speed of the feed rolls is hydraulically adjustable.

The disc is driven through a speed reducer and sprocket/roller chain drive system by a 175-horsepower diesel engine. A slip clutch between the engine and the speed reducer is adjusted to

transmit about 100 horsepower. Sprockets made it possible to adjust the no-load cutter disc speed to 156, 218, and 311 revolutions per minute (rpm).

Laboratory Testing

To determine horsepower and energy requirements at the cutter disc for chunking, torque was measured with a strain gauge transducer mounted between the driving sprocket and cutter disc shaft (fig. 3). An oscillograph recorded the torque signal and cutter disc rpm during chunking. Horsepower and energy then were calculated from the torque and disc rpm and correlated to log diameter, volume chunked, and wood specific gravity.

We investigated cutter disc rotational speed and feed rate (as determined by feed roll speed), as well as the various material properties such as specific gravity, moisture content, and log diameter. Both individual logs and bundled small stems were chunked experimentally. All tests were done using 1/4-inch-thick blades except one specific series to determine the effect of using 3/8-inch-thick blades. We also evaluated the effect of chunking frozen wood that was stored in a cold room at 0 degrees F until the heartwood reached 10 degrees F or below. Only key results are summarized here; the complete results of this work are covered in other published works (Arola *et al.* 1983a, 1983b, 1985).

Laboratory chunking of individual logs was limited to straight, 8-foot-long bolts with fairly uniform diameters (less than 9 inches). Bolt uniformity made it easier to determine the machine's performance as measured by dependent factors such as power and energy requirements versus the independent factors of log diameter and the calculated volume of solid wood chunked.

Preliminary testing revealed that the machine performed well at a nominal no-load cutter disc speed of 220 rpm. Good results also were achieved when the feed rolls were adjusted to give a no-load workpiece lineal feed rate of 245 feet per minute.

The following common, naturally grown, Lake States species were tested: quaking aspen (*Populus tremuloides*), red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), white birch (*Betula papyrifera*), jack pine (*Pinus banksiana*), and balsam fir (*Abies balsamea*). We also tested one intensively cultured species: *Populus* 'Tristis'. These seven species cover a wide range of wood densities and made it possible to correlate power and energy against wood specific gravity.

All material was chunked in a green condition (as would normally be done in a whole-tree harvesting operation), and as-chunked moisture content was recorded. Test bolt diameters ranged between 5 and 8-1/2 inches. Samples of the chunked output were measured for particle length, and the bulk density of the chunkwood was determined.

RESULTS

Energy Requirements

A conventional chipper produces particles ranging from 3/4 to 1 inch long in the fiber direction. With the chunker adjusted to sever particles from 2 to 4-1/2 inches long in the fiber direction, the volume of wood removed per cut is much greater with chunks than with conventional chips. The reported units of energy are normalized to include volume—for example, horsepower-minutes per cubic foot (hp-min/cu ft). We reemphasize that the energy and power requirements reported in this paper are based on measurements made at the shaft driving the cutter disc.

The mean energy requirements for chunking ranged from 1.2 hp-min/cu ft for the species with the lowest specific gravity (*Populus* 'Tristis' and balsam fir) to 2.5 hp-min/cu ft for the species with the highest specific gravity (sugar maple) (table 1). An analysis of variance showed specific gravity (species) to be significant at the 99-percent level. A single linear regression of energy in terms of specific gravity had an r^2 value of about 72 (fig. 4). Log diameter was not significant because energy already was normalized for this factor.

Table 1.—*Mean experimental energy requirements for chunking as determined at the cutter disc*

Species	Mean energy			
	English units		Metric units	
	hp-min/cu ft	*hp-hr/green ton*	*kw-min/cu m*	*kw-hr/green metric ton*
Populus 'Tristis'	1.2	1.1	32	0.6
Balsam fir	1.2	0.8	32	0.6
Aspen	1.4	0.9	37	0.8
Jack pine	1.6	1.1	43	0.9
White birch	1.8	1.0	48	0.8
Red maple	2.1	1.3	56	1.1
Sugar maple	2.5	1.4	67	1.2

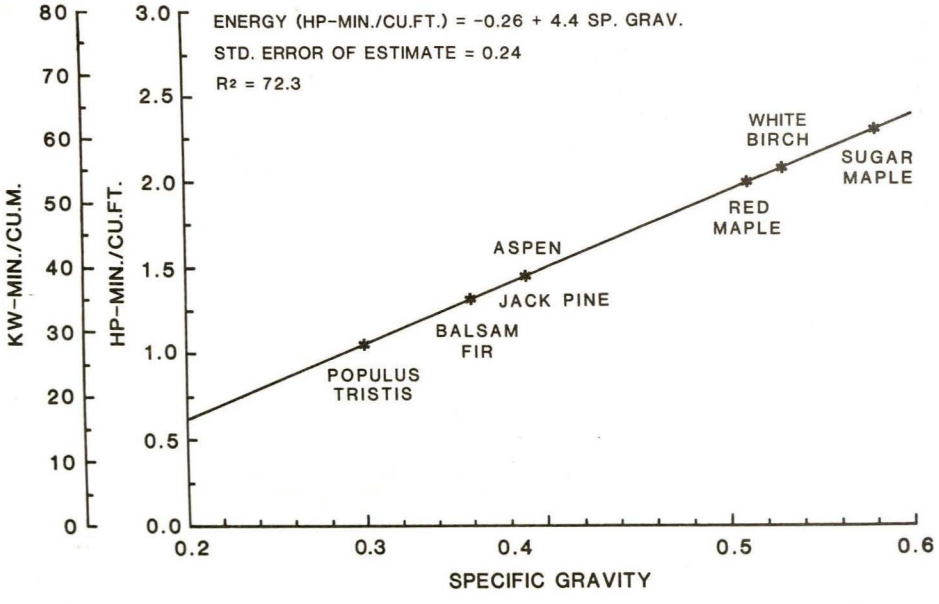


Figure 4.—*Energy required to chunk wood from several tree species with different specific gravities.*

By comparing chunking energy requirements determined in this work with chipping requirements determined in a similar manner for several of the same species (Papworth and Erickson 1966), we see that chunking energy at the cutter is only 30 to 40 percent of the chipping energy as shown in the following tabulation. Expressed differently, at the cutter disc, specific chunking energy was 60 to 70 percent less than specific chipping energy.

Species	Energy		Energy ratio (Chunks/chips)
	Chunking	Chipping[1]	
	(Hp-min/cu ft)		(Percent)
Aspen	1.4	3.8	37
Red maple	2.1	5.5	38
Sugar maple	2.5	7.6	33

[1]*Papworth and Erickson 1966.*

Power Requirements

An analysis of variance showed that both specific gravity (species) and log diameter had a significant effect on power requirements. We developed a linear regression equation in terms of bolt diameter and a species correction factor that takes into account specific gravity. Based on this regression, we prepared a family of linear plots for the seven species tested to predict power requirements at the chunker's cutter disc when using 1/4-inch-thick blades (fig. 5).

Frozen Wood

Tests with frozen aspen and red maple showed no surprises—more horsepower and energy were required to chunk frozen wood, and the production rate was somewhat lower than with green wood. The energy required to chunk frozen aspen was 2.3 hp-min/cu ft, which is 64 percent greater than for green, unfrozen aspen. Frozen red maple required 2.6 hp-min/cu ft, 24 percent more than for green, unfrozen maple.

Blade Thickness

More energy was required to chunk aspen and red maple with 3/8-inch-thick blades than with 1/4-inch-thick blades. The increase was 0.7 hp-min/cu ft, or 52 percent, for aspen and 0.6 hp-min/cu ft, or 27 percent, for red maple. We did not test thicker blades; however, we anticipate that energy requirements would continue to increase as blade thickness increases, based on prior research to crosscut shear roundwood bolts with blades of several thicknesses (Arola 1971).

Production Rate

The theoretical solid wood production rate for a wood chunking machine similar to the unit described here is given by the following:

$$V = \frac{D^2LNRA}{2{,}200}$$

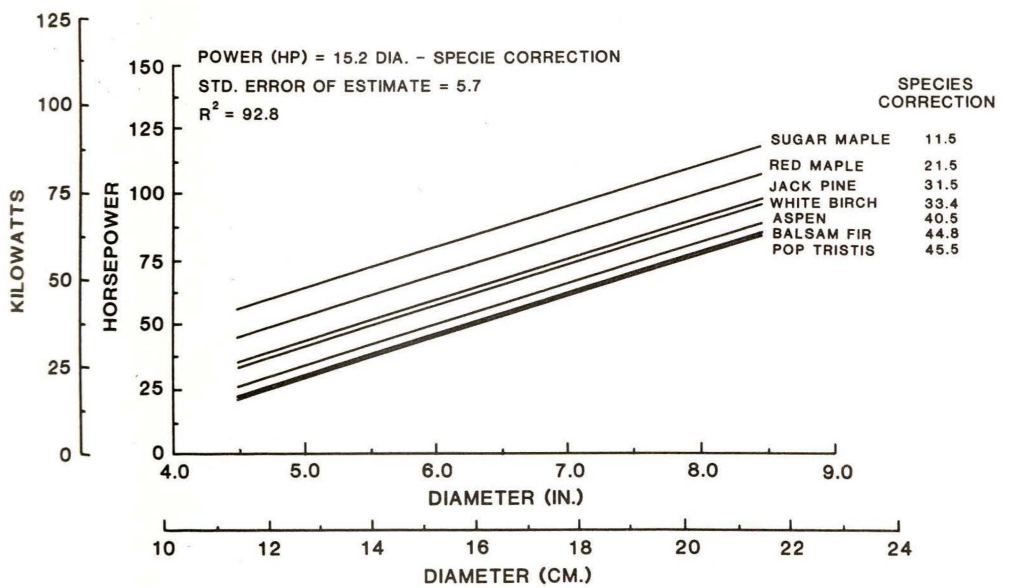


Figure 5.—*Power required to chunk logs of different diameters from several tree species.*

where:

V = volumetric chunkwood production (cu ft/min),
D = bolt diameter (inches),
L = length of particle removed per cut (inches),
N = number of cuts per revolution,
R = revolutions per minute, and
A = percent availability divided by 100.

As an example, assume 8-inch-diameter logs are being chunked with a three-bladed machine operating at 200 rpm, the machine is being fed 60 percent of the time, and the length of chunks is 3 inches:

$$V = \frac{(8)^2(3)(3)(200)(0.60)}{2{,}200}$$

$$V = 31.4 \text{ cu ft/min.}$$

The above formula expresses the theoretical solid wood production rate of any wood chunker. If the no-load cutter disc speed were used in the formula, the theoretical production rate would be higher than what would be obtained under actual operating conditions. The reason for the difference is that the cutter disc slows down as the chunks are severed—how much it slows down depends on how difficult the wood is to chunk (and the flywheel energy on the cutter disc). High-density species will slow the cutter disc more than low-density species.

The production rate of our laboratory involuted single-disc wood chunker with different diameter logs was determined experimentally, and a family of linear regression plots was developed for wood having different specific gravities (fig. 6). Keep in mind that the production rate with uniform diameter logs would be greater than with entire trees of an equal butt diameter.

Chunkwood

Our experimental machine consistently produced chunks in the desired target range. Average chunk length in the par fiber direction was 3.6 inches for softwoods; for some unknown reason, it was slightly greater for hardwoods. Smaller diameter bolts yielded slightly longer chunks, perhaps because bolts whose diameters are smaller than the infeed opening are not immediately engaged by the cutter. Therefore, they allow more time for the bolt to travel between the completion of one cut and the beginning of the next. The average chunkwood bulk density for the several species tested ranged from 20 to 25 pounds/cubic foot (lbs/cu ft), with an all species average of about 22 lbs/cu ft as shown in the following tabulation on page 53.

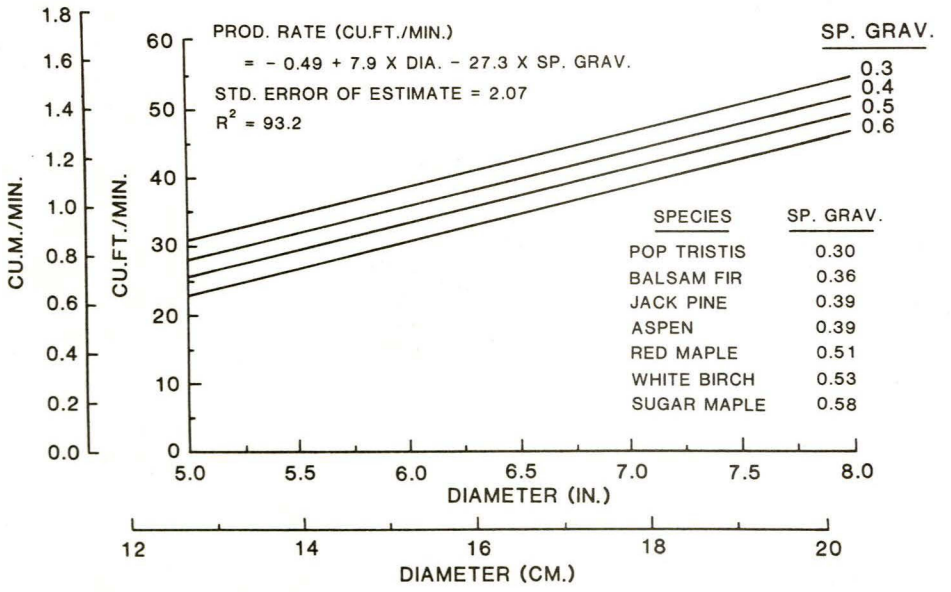


Figure 6.—*Production rate of the experimental wood chunker when chunking logs with different diameters.*

Species	Test bolt: Specific gravity	Test bolt: Moisture content (Percent)	Chunkwood: Bulk density (lb/cu ft)
Populus 'Tristis'	0.30	47	-
Balsam fir	.36	57	21.8
Aspen	.39	50	19.5
Jack pine	.39	52	22.8
Red maple	.51	40	22.6
White birch	.53	45	22.1
Sugar maple	.58	38	24.4
Average			22.2

Bundled Stems

Several countries have been focusing on harvesting intensively cultured trees under short rotations. Some approaches specify harvesting trees as small as 1 inch in diameter, but conventional chippers do not perform well with such small stems. They tend to drag the stems over the anvil and produce long "banana peels." Also, harvesting and processing costs escalate very rapidly when handling individual small stems. One concept to reduce costs is to bundle the small stems when they are harvested.

The purpose of these tests was to determine how our involuted single-disc chunking machine performed on bundled small stems (Arola *et al.* 1985) (fig. 7). Individual stems of aspen, tag alder, and hybrid *Populus* were sorted into two arbitrary diameter groupings—a 1-inch-diameter group that included stems equal to or less than 1.6 inches and a 2-inch-diameter group including those stems greater than 1.6 inches. The largest stems in the latter group did not exceed 2.5 inches in diameter. After the individual stems were grouped into two diameter classes, they were prepared, using a special jig, into about 8-inch-diameter bundles, and each bundle was coded, weighed, and then chunked. After chunking, particle samples were taken to determine moisture content, specific gravity, and chunk length. As was done with solid bolts, average power, energy, and production rates were calculated from the raw data, and the results were summarized (fig. 8).

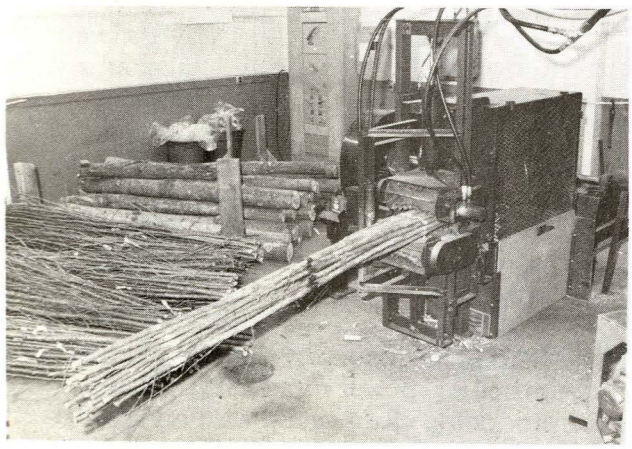


Figure 7.—*Chunking bundled stems with the involuted single-disc wood chunker.*

Our prototype wood chunker worked exceptionally well to reduce bundled stems into billets ranging from 3-1/2 to 4 inches long (fig. 9). The production rates ranged from 17 to 31 cubic feet per minute of solid wood. The mean power

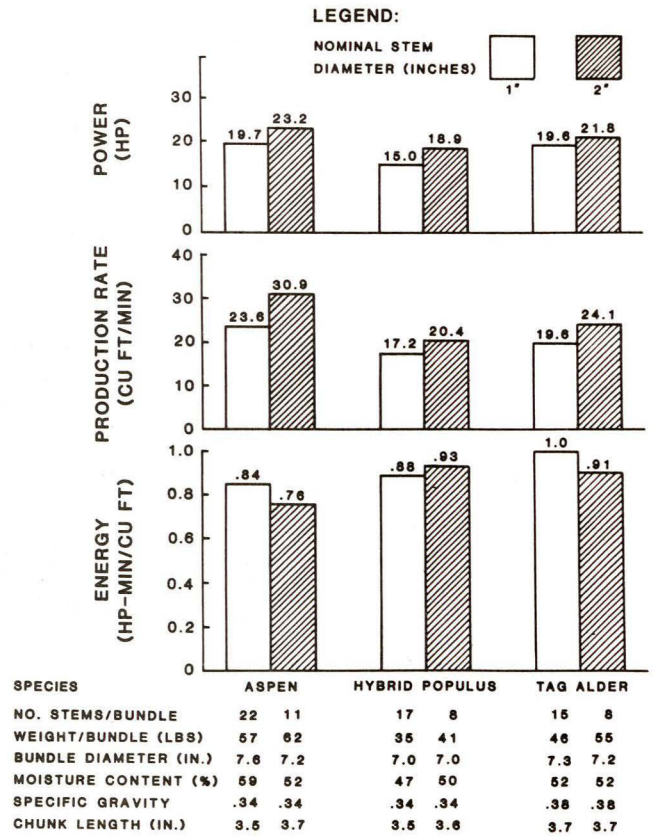


Figure 8.—*Power, energy, and production rates for chunking bundled stems of three species with the involuted single-disc wood chunker.*

Figure 9.—*Billets produced from chunking bundled stems with the involuted single-disc wood chunker.*

requirements were from 15 to 23 horsepower, and the specific energy requirements ranged from 3/4 to 1 hp-min/cu ft.

These results are unique to our laboratory version of the involuted single-disc chunker. The results, particularly those pertaining to power and energy requirements, do not represent the requirements for a field wood chunking machine.

Production Studies of Field Prototypes

Production studies were conducted with the Houghton and Missoula prototype wood chunkers in a field setting as a part of a project to build forest roads with chunkwood (fig. 10). Detailed time study data are presented only for the Missoula chunker operating in a whole-tree harvesting situation in a forest stand containing mostly jack pine with trace amounts of aspen (fig. 11). Trees with butt diameters up to 12 inches were skidded to the chunker. Based on 15 separate observations, with an observation being a 20-cubic yard truckload, the production rate ranged from 22.6 to 34.9 green tons per productive hour with a mean rate of 28.6 tons per hour. The mean weight of chunks in a full truckload was 5.4 green tons with a standard deviation of 0.2 ton. It took an average of 2.1 minutes to produce 1 green ton of chunks—1.4 minute of this time the chunker was actually producing chunks, and the remaining 0.7 minute the operator was either reaching for another tree or cleaning debris from around the infeed opening with the slide boom loader.

Production could have been increased if the operator was ready to engage the next tree in the chunker's feed rolls before the previous tree had been chunked completely—in other words, maintaining as close to 100-percent feed as possible. It is unproductive for the operator to wait for a tree to finish being chunked before reaching for the next tree.

On a mixed hardwood site containing mostly sugar maple and aspen, the mean production rate with the Missoula chunker was 26 green tons per productive machine hour based on 30 observations (truckloads). Most of the hardwood trees chunked were less than 10 inches in diameter. On the same mixed hardwood site, the Houghton chunker, with a capacity limited to about 8-inch-diameter trees, had a mean production rate of 14 green tons per productive hour. These production rates should be used with discretion. We believe that the production rate of future, commercial, whole-tree chunking machines can be much greater than that of our demonstration units. Similarly, it is unwise to compare production rates of the demonstration machines to commercial whole-tree chippers.

CONCLUDING COMMENTS

The three wood chunking machines introduced through Forest Service research have yet to reach commercialization in the U.S. The first machine, called a helical-head chipper (chunker), though not commercially available in the U.S., has been marketed for several years in Scandinavia as a conescrew chipper/chunker under a separate Finnish patent. The second U.S. machine, the involuted single-disc chunker, is currently in the infant stages of commercial development by a U.S. firm. The third machine, a multi-product wood processor, has been developed only to the stage of a laboratory prototype.

Basic engineering information presented in this paper, in particular, power and energy requirements for producing chunkwood with an involuted single-disc chunker, should prove useful to

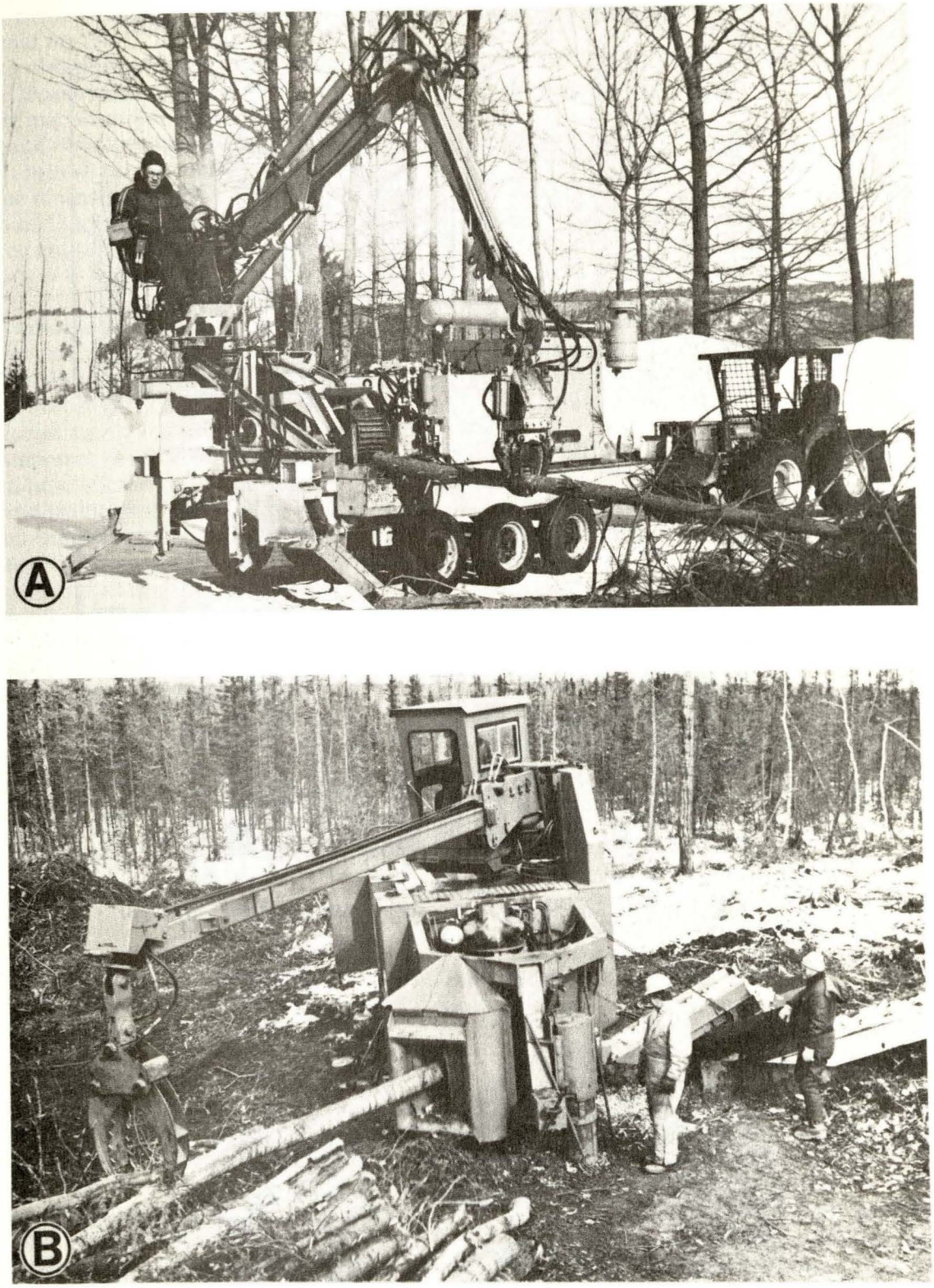


Figure 10.—*USDA Forest Service demonstration prototype wood chunking machines: A. Houghton chunker; B. Missoula chunker.*

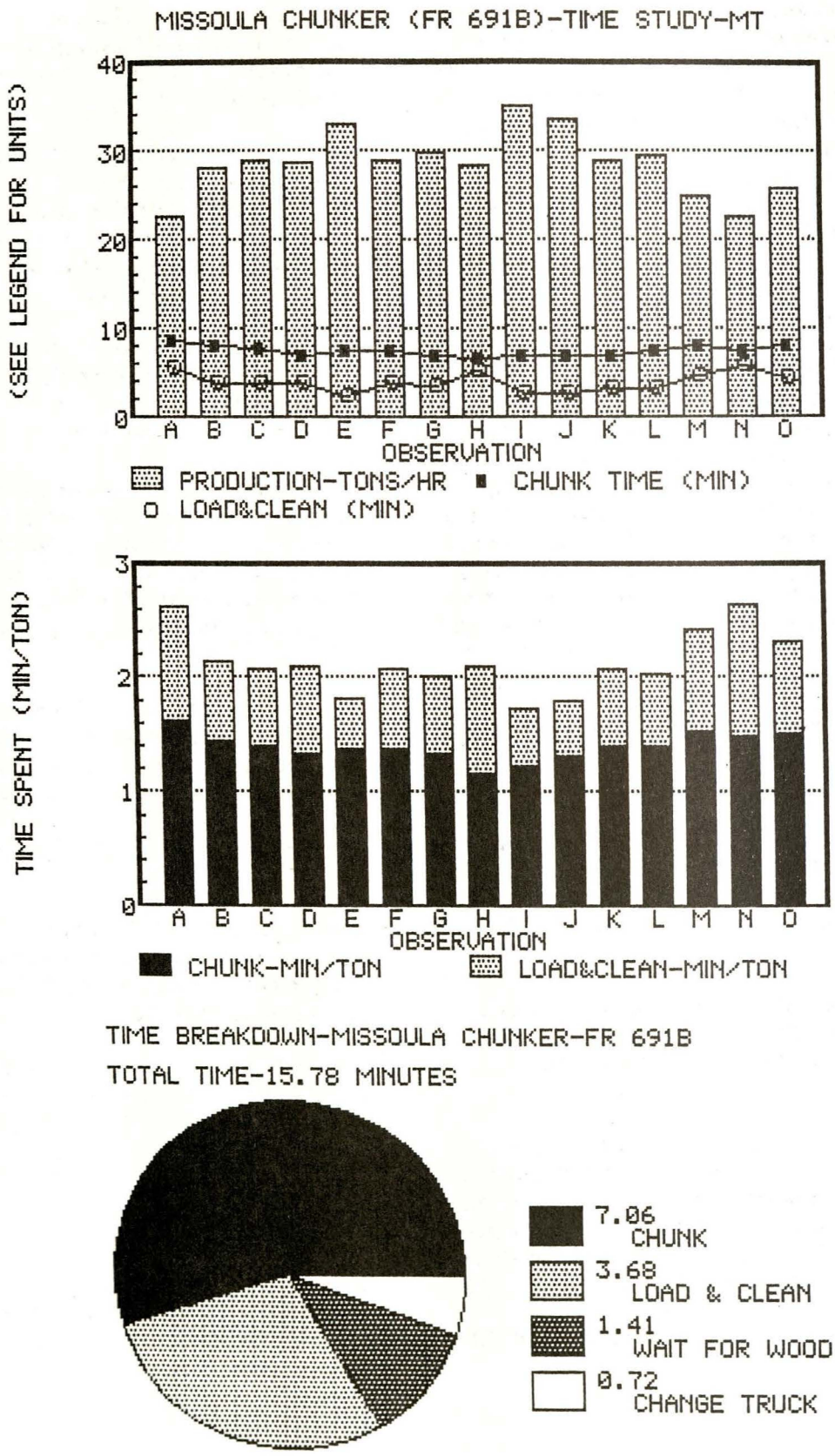


Figure 11.—*Productivity and time breakdown when chunking with the Missoula field demonstration prototype.*

machine manufacturers to aid in the design of commercial models of this machine. Data presented on chunkwood production rates with the U.S. field demonstration prototype wood chunking machines can be used for first-order estimates of chunker productivity. There is no reason to believe that commercial models of the same type of wood chunking machine would not have productivity levels comparable to that of a whole-tree chipper having an equivalent diameter limit.

Growing international interest to use chunkwood as an alternative form of forestry biomass fuel, as a feedstock for manufacturing composite flake products, and as a roadbuilding material for low-volume forest roads will prompt further commercial development of wood chunking machines. The main justification to use chunkwood in lieu of the more traditional wood chips will be found in the fact that chunkwood offers some unique characteristics because of its distinctly different particle size and shape that offer advantages to the intended application that ordinary chips do not offer. Ultimately, the potential user must decide which alternative particles, chunks or chips, are best for the particular application.

LITERATURE CITED

Arola, Rodger A. 1971. **Crosscut shearing of roundwood bolts**. Res. Pap. NC-68. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 21 p.

Arola, Rodger A.; Sturos, Joseph B. 1982. **A portable chunking machine**. Res. Note WO-11. Washington, DC: U.S. Department of Agriculture, Forest Service. 4 p.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A. 1983a. **Prototype wood chunker used on *Populus* 'Tristis'.** In: Hansen, Edward A., comp. Intensive plantation culture: 12 years research; 1983 January 26-27; Rhinelander, WI. Gen. Tech. Rep. NC-91. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 125-130.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A. 1985. **Chunking bundled small-diameter stems**. Forest Products Journal. 35(4): 40-42.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A.; Matson, Edsel D. 1982. **A new machine for producing chunkwood**. Res. Pap. NC-211. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 8 p.

Arola, Rodger A.; Winsauer, Sharon A.; Radcliffe, Robert C.; Smith, Martyn R. 1983b. **Chunkwood production: a new concept**. Forest Products Journal. 33(7/8): 43-51.

Barwise, Robert D.; Arola, Rodger A.; Erickson, John R., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1977. **Helical head comminuting shear**. U.S. patent 4,053,004. October 11. 10 p. Int. Cl.^{2} B27C 1/08. U.S. Cl. 144/162 R.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. **Involuted disc slicer**. U.S. patent 4,431,039. February 14. 11 p. Int. Cl.^{3} B27L 11/02. U.S. Cl. 144/176.

Erickson, John R. 1976. **Exploratory trials with a spiral-head chipper to make hardwood "fingerling" chips for ring flakers**. Forest Products Journal. 26(6): 50-53.

Gardner, Rulon B.; Schaffer, Erwin L.; Erickson, John R. 1978. **Converting forest residue to structural flakeboard - the fingerling concept**. Res. Pap. INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 31 p.

Haataja, Bruce A.; Adams, Roy D.; Arola, Rodger A. [1984]. **Total tree chunkwood as raw material for flake products**. In: Corcoran, Thomas J.; Gill, Douglas R., eds. COFE/IUFRO

1984: Proceedings of a symposium; 1984 August 11-18; Orono, ME; Fredericton, Canada. SAF Publ. 84-13. Orono, ME: University of Maine: 157-163.

Hakkila, Pentti; Kalaja, Hannu. 1981. **KOPO block chip system**. Folia Forestalia 467. Helsinki, Finland: The Finnish Forest Research Institute. 24 p.

Kangas, Vernon W.; Kangas, Roy J.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1986. **Multi-product wood processor**. U.S. patent 4,607,672. August 26. 9 p. Int. Cl.^{4} B27C 9/00. U.S. Cl. 144/2R.

Nurmi, Juha. 1986. **Palahakkeen ja hakkeen valmistus kartioruuvihakkurilla: Chunking and chipping with conescrew chipper**. Folia Forestalia 659. Helsinki, Finland: The Finnish Forest Research Institute. 23 p.

Papworth, R.L.; Erickson, J.R. 1966. **Power requirements for producing wood chips**. Forest Products Journal. 16(10): 31-36.

Sturos, Joseph B. 1989. **Teardrop chunker performance**. Res. Pap. NC-285. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p. (Also in: 1988. In: Production, storage and utilization of wood fuels; Proceedings of IEA/BE conference task 3/activity 6 and 7; 1988 December 6-7; Uppsala, Sweden. Garpenberg, Sweden: The Swedish University of Agricultural Sciences, Department of Operational Efficiency; 1: 195-208.)

U.S. Department of Agriculture, Forest Service. 1978. **Structural flakeboard from forest residues: Proceedings of a symposium;** 1978 June 6-8; Kansas City, MO. Gen. Tech. Rep. WO-5. Washington, DC: U.S. Department of Agriculture, Forest Service. 241 p.

Airflow Resistance of Chunkwood[1]

Joseph B. Sturos[2]

Abstract.—Continued interest in biomass for energy, together with efforts to improve the utilization of available biomass, has led to the introduction of a new fuel form called "chunkwood." Chunkwood particles are pieces of wood that are much larger than whole-tree chips and require less energy to produce, have a higher bulk density, and can dry faster under certain conditions. The purpose of this study was to define several variations of chunkwood, document their character, and determine their resistance to airflow. These types of data are needed to design or select chunkwood combustion and drying systems or equipment. Three chunkwood variations were studied—whole-tree, delimbed, and reduced chunks. In addition, chips were included for comparison. The test method consisted of measuring the pressure drop developed across a given quantity of material when subjected to a known airflow rate. A 15-square foot test chamber was used to subject 2- to 4-foot depths of material to six airflow rates ranging from 50 to 1,000 cubic feet per minute. Delimbed chunks had the least resistance, whole-tree chunks had the highest resistance, and reduced chunks' resistance was between the two. All three chunkwood forms exhibited less resistance than chips. Compared to chips, chunks developed from 40 to 77 percent less pressure drop.

INTRODUCTION

The uncertainties of cost, availability, and pollution regulations associated with conventional fuels such as coal and oil continue to stimulate interest in using biomass for energy. In the past, sawmill residues have been a primary source of biomass material. More recently, the invention of whole-tree chippers has led to widespread use of whole-tree chips for fuel. However, whole-tree chips have certain drawbacks when used as fuel. They require considerable energy to produce, have a low bulk density, and pack closely in storage piles. This close packing inhibits natural drying and promotes microbial activity and deterioration. In gasifiers and combustors using natural drafts, the chips' tendency to pack can restrict airflow necessary for complete combustion. And when burned in large industrial combustors, the chips' light weight, coupled with the high flue velocities, tends to produce high particulate emissions. These problems associated with the energy use of whole-tree chips have led to the introduction of chunkwood as a new biomass fuel form.

Chunkwood particles are much larger than chips. Their size ranges from pieces the size of a finger up to disks the diameter of the original tree (fig. 1). The larger chunkwood blocks have a semifractured character which, when coupled with the large void spaces that naturally occur

[1]*Paper presented at the International Energy Agency/ Bioenergy Conference, Task III/Activity 6 and 7 "Production, storage, and utilization of wood fuels." [The Swedish University of Agricultural Sciences, Uppsala, Sweden, December 6-7, 1988.] Also published in March 1989 by the* Forest Products Journal.

[2]*Joseph B. Sturos is Mechanical Engineering Technician, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

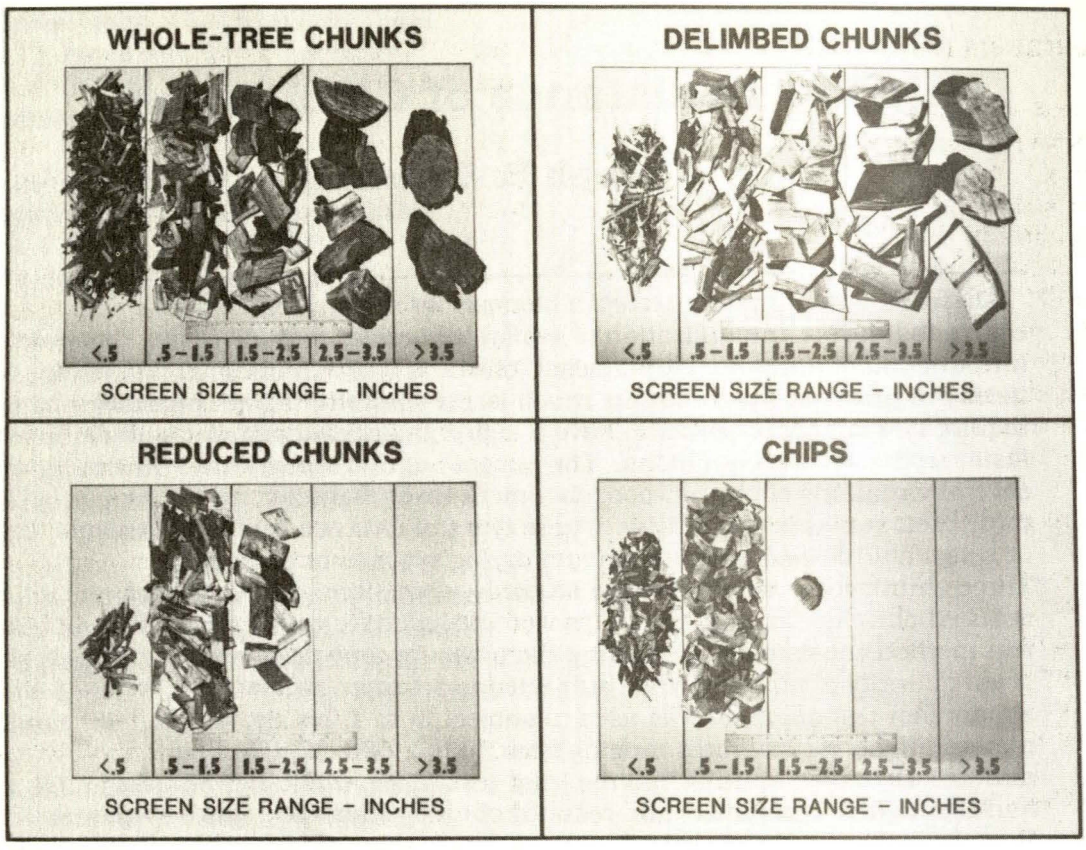


Figure 1.—*Typical particles for five screen size ranges.*

between the particles, allows air to easily infiltrate and promotes faster drying (Nurmi 1986, Sturos 1984, Sturos *et al.* 1983). It is hypothesized that the more porous chunkwood fuel bed will result in more complete combustion. This paper defines several variations of chunkwood, documents their character, and develops basic engineering data on the resistance of chunkwood to unheated ambient airflow for a wide range of airflow rates.

The chunkwood concept emerged from a USDA Forest Service national research program aimed at improving the utilization of our forests (Arola *et al.* 1982, Erickson 1976). The original idea was to reduce small-diameter trees and forest residues into more manageable 2- to 3-inch-long pieces (or chunks) of wood that could be used to make flakes for the manufacture of flakeboard or other composite wood products. More recently, the definition of chunkwood has been expanded to include all pieces of wood mechanically severed from whole trees or forest residues and ranging from 2 to 12 inches long in the fiber direction and any cross section, including round pieces the full diameter of the tree.

When considering biomass for energy, the movement of air plays an important role in two areas—drying and combustion. Dried wood chips develop less fungal contamination when stored and flow better in freezing weather (Riley and Drechsel 1983). Dried fuels also have higher heating values, higher boiler efficiencies, and reduced stack emissions (Haygreen 1981). A common method of drying is to blow air through the material during storage.

To properly design drying and combustion systems, basic data are required on the resistance of the fuel to airflow. Although airflow resistance data have been published for agricultural products, sawdust, and wood chips (American Society of Agricultural Engineers 1984, Riley and Drechsel 1983, Suggs and Lanier 1985), no data are available for chunkwood.

RESEARCH METHOD AND MATERIALS

This study was a replicated experiment to determine the mean pressure drop of unheated ambient air flowing through chunkwood. The methods used were similar to those used by Suggs and Lanier (1985) in their study of airflow resistance of wood chips and sawdust and by Abrams and Fish (1982) using sweet potatoes. Basically, the method consisted of taking several depths of material, subjecting each to a range of airflow rates, measuring the pressure drop across the material, and then normalizing the data for depth and cross section.

Apparatus and Operational Description

The test apparatus used for this study consisted of three 4-foot x 4-foot x 4-foot vertically stacked plywood sections. The apparatus had an air supply diffuser section at the bottom, a sample retaining section in the middle, and a flow measuring section on top (fig. 2).

To minimize the effect of air leakage along the container side walls, Carman (1937) recommended a container-to-particle diameter ratio of at least 10 to 1. From previous unpublished work, we found that sugar maple chunkwood had an average cross-sectional dimension of about 3.7 inches. Using the 10 to 1 ratio, a 37-inch minimum cross-sectional dimension was indicated. However, for an added margin of safety, the basic inside cross section for the apparatus was increased to 46.5 inches x 46.5 inches (15.0 square feet net area).

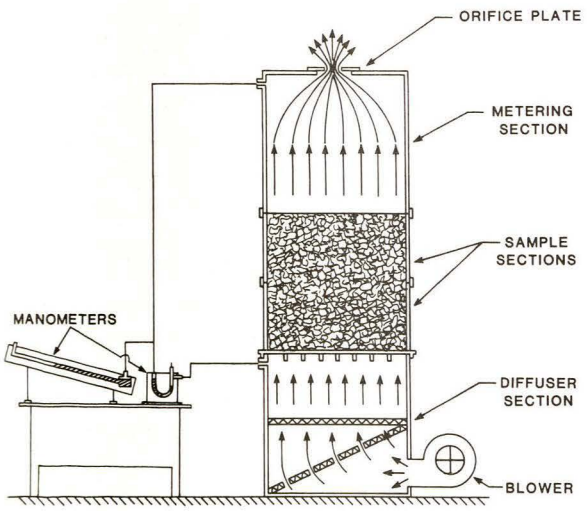


Figure 2.—*Test setup diagram.*

The bottom air supply section consisted of two parts: a blower and a diffusing chamber (fig. 2). The blower was driven by a variable speed hydraulic motor/pump combination. The diffusing chamber consisted of a steel angle iron frame covered with 1/2-inch plywood on the bottom and the sides and 1/2-inch mesh hardware cloth on the top. To carry the weight of the chunkwood, the hardware cloth was supported by a steel checkerboard-shaped grid. The grid spacing was about 12 inches on center and made of 1/8- x 2-3/4-inch flat stock welded on edge. Airflow approaching the sample was equalized by placing a combination of baffle plates and furnace filter material in two planes of the diffuser section (fig. 2). A hot wire anemometer was used to check for uniformity.

The middle sample section consisted of two 24-inch-high bottomless and topless frames stacked on top of each other (fig. 2). These retained the test material and made it possible to test material depths of 24 or 48 inches.

The top flow metering section was open on the bottom and equipped with a thin plate orifice flow meter on the top (fig. 2). To keep the blower horsepower requirements within the limits of the hydraulic system, the total static pressure was controlled by using different-sized orifice plates, depending on the flow rate required. Orifice diameters were 1.750, 3.500, 4.500, 6.750, and 8.125 inches.

The orifice plates were fabricated according to ASME Power Test Codes (American Society of Mechanical Engineers 1959). Airflow rates were calculated using the standard variable head flow meter equation (Tuve 1961):

$$Q = YMCA(2g\Delta h)^{.5}$$

where:

Q = flow rate,
Y = compressibility factor,
M = meter constant,
C = coefficient of discharge,
A = meter throat area,
g = acceleration of gravity, and
Δh = pressure drop across flow meter.

The discharge coefficient (C) for each of the orifice plates was experimentally determined to be 0.6. The coefficients were determined by adjusting the blower to the desired airflow rate (using a set of accurate flow nozzles placed in the blower inlet to measure actual airflow), measuring the pressure drop across the orifice, and calculating the discharge coefficient using the standard variable head flow meter equation listed on previous page. The maximum capacity of the flow nozzles was only 375 cubic feet per minute (cfm). Thus, the discharge coefficients for the three largest orifice plates were determined at settings below their intended flow rates. However, because they exhibited coefficients of 0.6, a commonly assumed value, it was deemed acceptable to use 0.6 for the higher flow rates.

The pressures in the system were sensed through two taps located in the side walls (fig. 2). The first tap was 3 inches below the orifice plate, and the second was 5 inches below the bottom surface of the test material. The pressure drop across the orifice plate was measured using a Meriam Model 40HA10 Inclined Manometer[3]; the pressure drop across the test material was measured using a Dwyer Microtector Hook Gage Manometer. System inlet and outlet air temperatures and relative humidities were measured using a Taylor Sling Psychometer placed in the airflow.

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others that may be suitable.*

Test Variables

The wood used for the study was obtained from freshly cut red maple (*Acer rubrum*) trees with butt diameters ranging from 6 to 8 inches. Three chunkwood variations—whole-tree, delimbed, and reduced chunks—were included in the study to cover a range of chunkwood possibilities. Whole-tree chunks (chunkwood made from whole trees) represent the most probable way chunkwood fuel would be used. Delimbed chunks (chunkwood made from tree boles) were chosen to represent a "clean" fuel, one that would have no foliage and fewer small particles to plug the voids between the larger particles. It would be preferable for storage and drying. Reduced chunks (chunkwood reduced in size by hammermilling and screened to remove fines (<0.2 inches) and oversized particles (>2 inches)) were used to represent a smaller and more uniform fingerling-type particle. We also included "clean" 3/4-inch pulp chips (chips made from delimbed boles) for comparison.

We tested two sample depths—24 and 48 inches—and six airflow rates—50, 200, 400, 600, 800, and 1,000 cfm (giving approach velocities of 3.3 to 66.7 cfm/square foot).

Test Procedure

The test was started with one 24-inch frame installed on top of the air supply section, and material was added until it was level with the top edge of the frame. The blower was adjusted for the various flow rates, starting at the lowest and progressing up to the highest. Four readings were taken at each setting about 1 minute apart, and the mean values were used to determine the pressure drop across both the flow meter and the test material. In addition, both inlet and outlet air wet and dry bulb temperatures were measured at both the beginning and end of each setting, and mean values were used. Next, the second 24-inch frame was installed, more material was added on top of the original material until a total of 48 inches was reached, and the above sequence was repeated. This entire procedure was replicated three times using fresh material each time.

The above procedure was followed first using whole-tree chunks and then delimbed chunks. Next, the delimbed chunks were reduced by hammermilling, screened, and tested as reduced chunks. Chips were tested last. For reasons of logistics and expediency, we did not randomize the tests.

During each loading, samples were taken and analyzed for moisture content and particle size distribution. After the loading was complete, the entire test fixture was weighed, and bulk densities were calculated.

RESULTS

Material Description

Initial bulk densities and moisture contents were determined for each of the materials tested (table 1). Bulk densities ranged from 22.4 pounds/cubic foot for delimbed chunks to 18.3 pounds/cubic foot for reduced chunks. The mean moisture contents for whole-tree chunks, delimbed chunks, and chips were fairly similar, ranging from 40 to 42 percent (all moisture contents listed are wet-weight basis); reduced chunks had a somewhat lower mean moisture content of 37 percent. (Note: If the moisture content for reduced chunks is adjusted up to that of chips (42 percent), its bulk density rises to 19.9 pounds/cubic foot, a value slightly higher than chips (19.6 pounds/cubic foot).)

The lower moisture content for the reduced chunks was attributed to two factors: first, the reduced chunks were made from the delimbed chunks used in the preceding tests which undoubtedly dried somewhat during the test, and second, the increased surface area that comes with reduction, coupled with the severe aeration during hammermilling and screening, caused additional drying.

To define the different particle types, a sample of each material was manually classified by size, and each fraction was analyzed for average particle weight and standard deviation. The device used to screen the material was a plywood board with a series of round holes cut into it. The holes ranged in diameter from 1/2 inch to 4 inches by 1/2-inch increments. The particles from each sample were sorted into groups based on the smallest hole that would pass the particle. Whole-tree chunks and delimbed chunks had similar distributions, with the whole-tree chunks having a slightly higher percent of the total weight in the smaller screen size categories (fig. 3). This higher fraction of small particles was undoubtedly due to the leaves, twigs, and small branches left on the trees when they were chunked. Most of the weight of both reduced chunks and chips was concentrated in the smaller screen size categories, with chips having the highest percentage of smaller particles. For example, 99 percent of the chip weight was made

Table 1.—*Initial bulk densities and moisture contents for chunkwood and chips*

	Whole-tree chunks	Delimbed chunks	Reduced chunks	Chips
		Bulk density (pound/foot^3)		
Mean	20.3	22.4	18.3	19.6
Range	19.6-20.1	21.8-22.9	18.0-18.6	19.1-20.0
		Moisture content[1] (percent)		
Mean	40	41	37	42
Range	38-43	39-42	36-37	40-43

[1]Wet-weight basis.

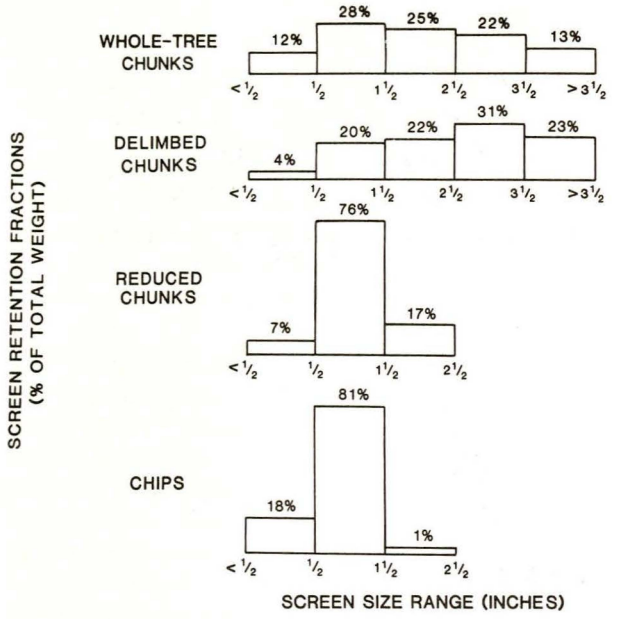


Figure 3.—*Particle size distributions for the chunkwood and chips tested. Percent of total weight retained for five screen size ranges.*

up of particles that passed through a 1-1/2-inch-diameter hole, compared to 83 percent for the reduced chunks, 40 percent for the whole-tree chunks, and only 24 percent for delimbed chunks.

Comparing the mean particle weights for the different screen size ranges revealed that whole-tree, delimbed, and reduced chunks all had similar values for the same size range, while chips are appreciably lighter (table 2). This is due to the short, thin, flat character of chips compared to the longer, thicker, and more square cross section of chunks.

Pressure Drop Test Results

The tests were conducted in a large, seasonally-heated shop building and extended over a period of 35 days (August 29, 1986 through October 2, 1986). The air blown through the test material was the ambient air from inside this building. Average dry and wet bulb temperatures and ranges for the test fixture's inlet and outlet are tabulated in the next column.

	Inlet temperature (°F)	Outlet temperature (°F)
Dry bulb		
Mean	68	61
Range	63 - 74	50 - 70
Wet bulb		
Mean	59	60
Range	52 - 64	49 - 69

Because tests were run using two different depths of material (24 inches and 48 inches), an Independent Groups T-test was used to determine if the pressure drop by depth was significant. No significant difference was found, so the 24- and 48-inch-depth data were combined and treated as one group.

A two-way analysis of variance showed a significant difference (at 99-percent confidence level) in pressure drop per unit depth (P) due to both material type and approach velocity (V) (airflow rate per unit cross section). Thus, each of the material types was treated as unique.

Previous work with agricultural products and wood chips has shown that this type of airflow data exhibits an exponential relation of the form $P=a*V^b$, where P and V are variables (pressure drop and approach velocity), and a and b are constants (Abrams and Fish 1982, Shedd 1953, Suggs and Lanier 1985). This equation plots as a straight line when logarithmically transformed.

To see if our data were of an exponential type, we plotted the data using log-log graph paper. This graph revealed that the data were not linear over the entire range of flow rates tested (fig. 4). The data appear linear from the maximum flow of 67 cfm/square foot down to 13 cfm/square foot. A linear par regression analysis was performed on the transformed variables (log (P) and log (V)) for this linear portion. The equations from this analysis are tabulated on page 66.

Table 2.—*Classification data for chunkwood and chips*

Screen size range (inches)	Fraction of total weight[1]	Mean particle weight[1]	Standard deviation
	Percent	*- - - Grams - - -*	
		Whole-tree chunks	
<0.5	12	-	-
0.5-1.5	28	2.2	2.6
1.5-2.5	25	17.0	14.5
2.5-3.5	22	76.9	34.4
>3.5	13	227	48
		Delimbed chunks	
<0.5	4	-	-
0.5-1.5	20	2.8	2.8
1.5-2.5	22	16.0	10.3
2.5-3.5	31	56.6	40.8
>3.5	23	233	48
		Reduced chunks	
<0.5	7	-	-
0.5-1.5	76	3.4	3.3
1.5-2.5	17	14.2	8.0
2.5-3.5	-		
>3.5	-		
		Chips	
<0.5	18	-	-
0.5-1.5	81	0.8	0.6
1.5-2.5	1	7.8	0
2.5-3.5	-		
>3.5	-		

[1]Oven-dry weight.

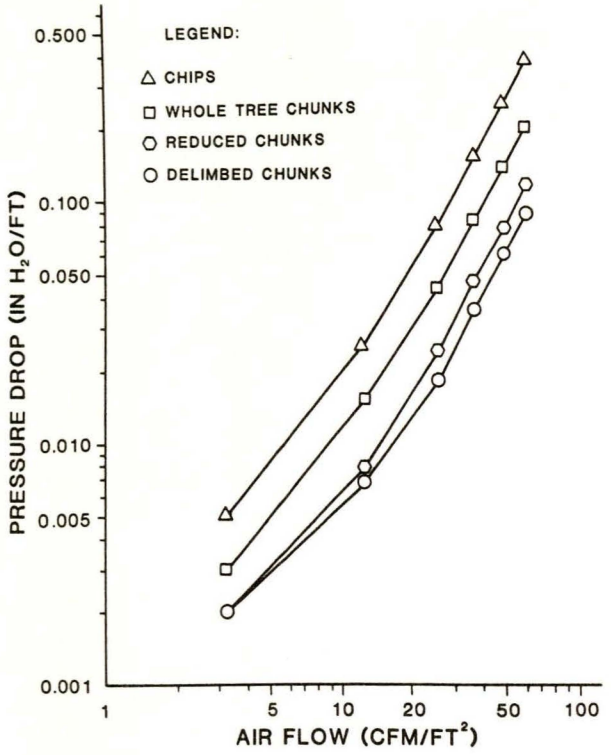


Figure 4.—*Log-log plot of pressure drop versus airflow for chips and for whole-tree, delimbed, and reduced chunks. Each data point represents the mean value of six replications.*

Material type	Regression equation	R^2
Whole-tree	log (P) = -3.692 + 1.637*log (V)	0.97
Delimbed	log (P) = -3.987 + 1.596*log (V)	0.98
Reduced	log (P) = -3.983 + 1.665*log (V)	0.99
Chips	log (P) = -3.494 + 1.680*log (V)	0.99

where:

P = inches of water pressure per foot depth of material, and

V = cubic feet of air per minute per square foot of cross section of material.

With all R^2 terms equaling or exceeding 0.97, the transformed variables for all of the materials exhibit a linear behavior.

Inverse transformation of the above equations gives exponential relations (applicable for V = 13 to 67 cfm/square foot):

Material type	Exponential equation
Whole-tree	$P = 0.000205*(V)^{1.637}$
Delimbed	$P = 0.000103*(V)^{1.596}$
Reduced	$P = 0.000104*(V)^{1.665}$
Chips	$P = 0.000321*(V)^{1.680}$

For comparison as well as a check of overall experimental accuracy, chips were included in the study. Our chip regression line agrees fairly well with that of Suggs and Lanier (1985) (fig. 5).

SUMMARY

Pressure drop per unit depth of material is basic engineering information important to both drying and combusting forest biomass fuels. To accelerate drying, forced air systems can be engineered so that fresh ambient or heated air is continuously introduced to remove moisture from the particles. Pressure drop data are needed to

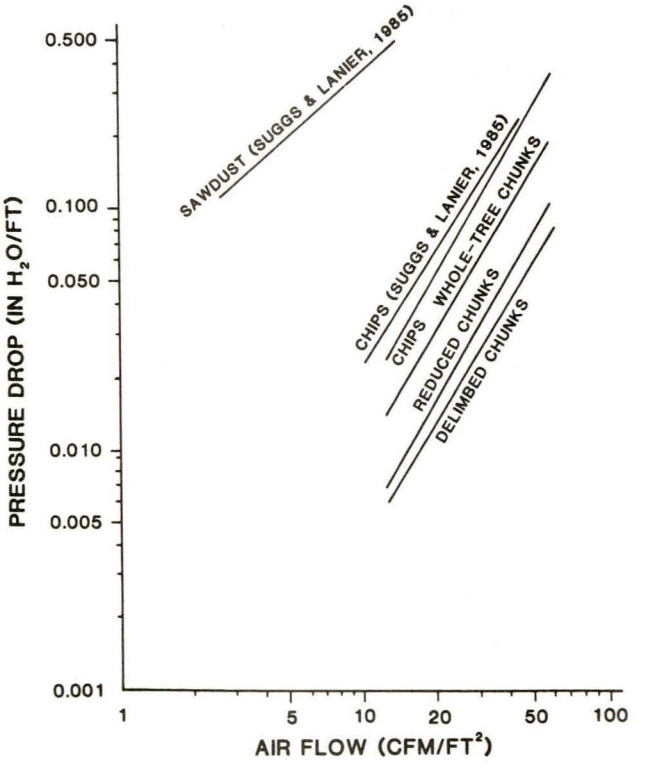


Figure 5.—*Comparison of the pressure drop regression lines for the chunkwood and chips tested and those published by Suggs and Lanier (1985) for green chips and sawdust.*

determine the optimum size of the blower so that proper airflow is obtained. In combustion systems that burn solid fuels in a thick bed or pile, pressure drop data are also needed to select equipment that will provide the correct amount of underfire combustion air. Pressure drop data are already available for sawdust and wood chip biomass fuels, and similar data are needed for chunkwood fuel. The objective of this study was to define several variations of chunkwood and determine their airflow resistance characteristics as determined by pressure drop per unit depth of material.

Three categories of chunkwood were tested: whole-tree, delimbed, and reduced chunks. In addition, conventional pulp chips were tested for comparison. We found significant differences in the airflow resistance between all three categories of chunkwood and between chunkwood and conventional-size pulp chips. Over the flow range tested (3.3 to 66 cfm/square foot), chunks exhibited appreciably less resistance to airflow than chips. Compared to chips, chunks developed from 40 to 77 percent less pressure drop depending on the material and flow rate.

METRIC CONVERSIONS

1 cubic foot = 0.0283 cubic meter
1 cubic foot/minute = 0.00047 cubic meter/second
1 foot = 0.3048 meter
1 foot/minute = 0.0051 meter/second
1 inch = 2.54 centimeters
1 pound = 0.4536 kilogram
1 pound/cubic foot = 16.02 kilograms/cubic meter
1 square foot = 0.0929 square meter

LITERATURE CITED

Abrams, C.F., Jr.; Fish, J.D., Jr. 1982. **Air flow resistance characteristics of bulk piled sweet potatoes**. Transactions of the American Society of Agricultural Engineers. 25(4): 1103-1106.

American Society of Agricultural Engineers. 1984. **Resistance of airflow through grains, seeds, and perforated metal sheets.** In: Standards - 1984, 31st ed. St. Joseph, MI: American Society of Agricultural Engineers: 79-83.

American Society of Mechanical Engineers. 1959. **Supplement to ASME power test codes, chapter 4: flow measurement, part 5: measurement of quality materials**. New York, NY: American Society of Mechanical Engineers. 91 p.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A.; Matson, Edsel D. 1982. **A new machine for producing chunkwood**. Res. Pap. NC-211. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 8 p.

Carman, P.C. 1937. **Fluid flow through granular beds**. Transactions of the Institution of Chemical Engineers. 15(1): 150-156.

Erickson, John R. 1976. **Exploratory trials with a spiral-head chipper to make hardwood "fingerling" chips for ring flakers**. Forest Products Journal. 26(6): 50-53.

Haygreen, John G. 1981. **Potential for compression drying of green wood chip fuel**. Forest Products Journal. 31(8): 43-54.

Nurmi, Juha. 1986. **Palahakkeen ja hakkeen valmistus kartioruuvihakkurilla: Chunking and chipping with conescrew chipper**. Folia Forestalia 659. Helsinki, Finland: The Finnish Forest Research Institute. 23 p.

Riley, John G.; Drechsel, Carl S. 1983. **Drying and storage of woody biomass fuels**. In: 1983 winter meeting of the American Society of Agricultural Engineers; 1983 December 13-16; Chicago, IL. Pap. 83-3560. St. Joseph, MI: American Society of Agricultural Engineers. 19 p.

Shedd, C.K. 1953. **Resistance of grains and seeds to air flow**. Agricultural Engineering. 34(9): 616-619.

Sturos, Joseph B. 1984. **Characterization and air drying of chunkwood and chips**. Res. Note NC-308. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 6 p.

Sturos, Joseph B.; Coyer, Lynne A.; Arola, Rodger A. 1983. **Air drying of chunkwood and chips**. Res. Note NC-293. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.

Suggs, C.W.; Lanier, Alicia. 1985. **Resistance of wood chips and sawdust to airflow**. Transactions of the American Society of Agricultural Engineers. 28(1): 293-301.

Tuve, G.L. 1961. **Mechanical engineering experimentation**. New York, NY: McGraw-Hill: 247. Chapter 8: Fluid flow and fluid dynamics.

Teardrop Chunker Performance[1]

Joseph B. Sturos[2]

Abstract.—In our continuing effort to improve the utilization of low-valued forest resources, we have invented the Multi-Product Wood Processor, a new wood chunking machine. The Multi-Product Wood Processor or "Teardrop Chunker" is a rotating, cylindrical drum with two sharp-edged, teardrop-shaped cutter openings. Short chunks are produced when a log is fed into the rotating drum openings. Chunk length is controlled by the log feed rate and the drum speed. Machine output, cutter power, and energy requirements were evaluated for two species, aspen and sugar maple, and for two chunk lengths, short and long.

INTRODUCTION

Researchers at the Forestry Sciences Laboratory in Houghton, Michigan, have continued to explore chunking alternatives to enhance utilization of logging residues and small-diameter trees from thinnings and poor-quality stands. They have invented and patented three different chunking machines—the Helical Head Comminuting Shear (Arola and Sturos 1982, Barwise *et al.* 1977), the Involuted Disc Slicer (Arola *et al.* 1982, Barwise *et al.* 1984), and most recently the Multi-Product Wood Processor (Kangas *et al.* 1986) (fig. 1). The Multi-Product Wood Processor or "Teardrop Chunker" is a small machine designed to chunk trees less than 7 inches in diameter. The Teardrop Chunker produces a unique form of chunkwood. Compared to the Helical Head Chipper and the Involuted Disc Slicer, which produce fractured, broken chunks of wood (fig. 2), the Teardrop Chunker produces solid wood chunks that are primarily short, round log sections (fig. 3). As with the Involuted Disc Slicer, the length of the chunk (parallel to the fiber direction) is adjustable.

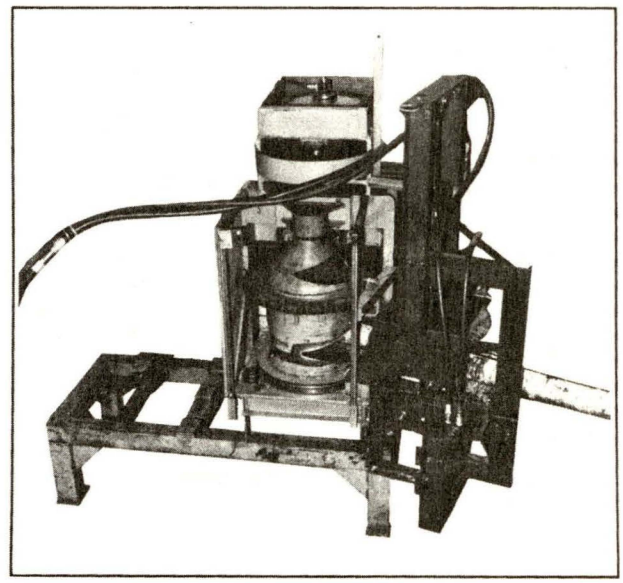


Figure 1.—*The Multi-Product Wood Processor or "Teardrop Chunker."*

[1]*Paper presented at the International Energy Agency/Bioenergy Conference, Task III/Activity 6 and 7 "Production, storage, and utilization of wood fuels." [The Swedish University of Agricultural Sciences, Uppsala, Sweden, December 6-7, 1988.] Also published in 1989 as North Central Forest Experiment Station Research Paper NC-285.*

[2]*Joseph B. Sturos is Mechanical Engineering Technician, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

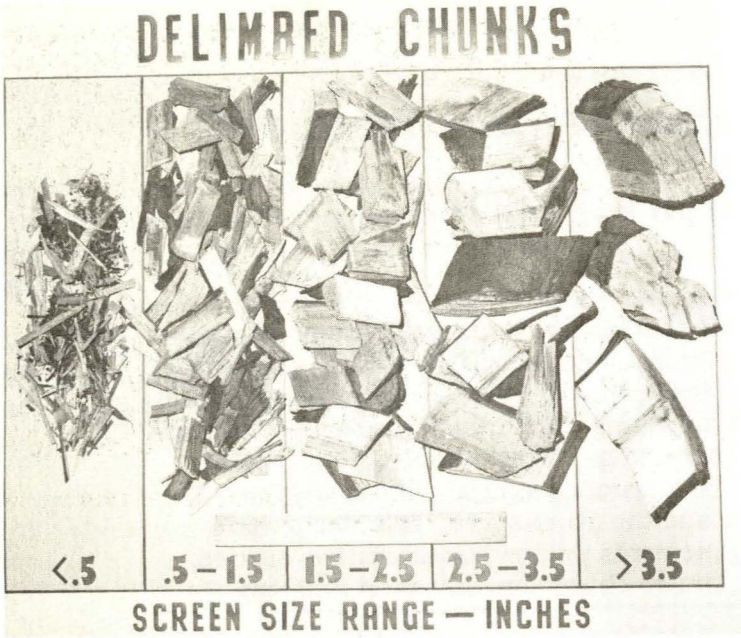


Figure 2.—*Typical particles produced by the Involuted Disc Slicer using delimbed sugar maple logs. (Volumes shown are approximate proportions.)*

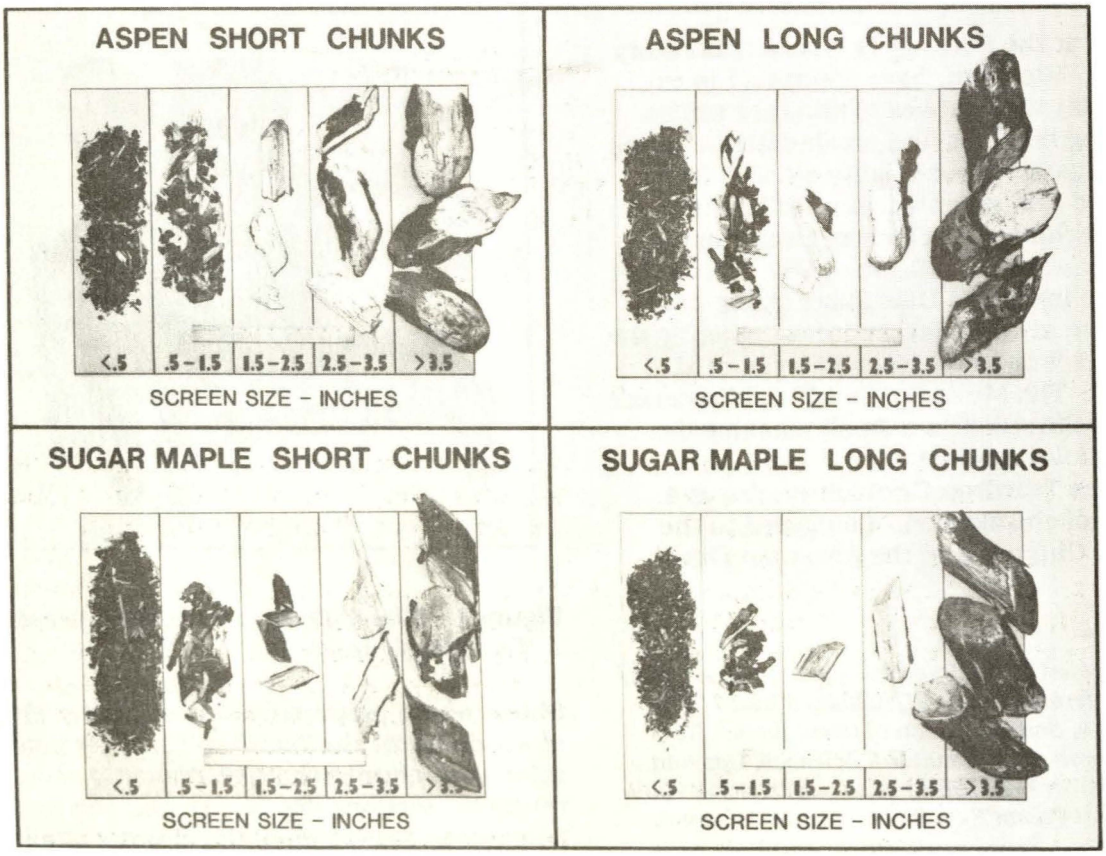


Figure 3.—*Typical particles produced by the Teardrop Chunker using two species, aspen and sugar maple, and two chunk lengths, short and long. (Volumes shown are approximate proportions.)*

A limited study was conducted to determine output, power, and energy characteristics of the Teardrop Chunker. This paper reports those findings.

MACHINE DESCRIPTION

The experimental Teardrop Chunker consists of four main parts: a rotating cutting drum, a feed mechanism, a flywheel, and a hydraulic power supply (fig. 4). The drum has two teardrop-shaped openings 180 degrees apart with sharpened edges that repeatedly slice off the end of a log as it is propelled into the openings by the feed rollers (fig. 5). The drum rotates vertically, which allows the chunks to drop out of the bottom by gravity. Chunk length is controlled by changing

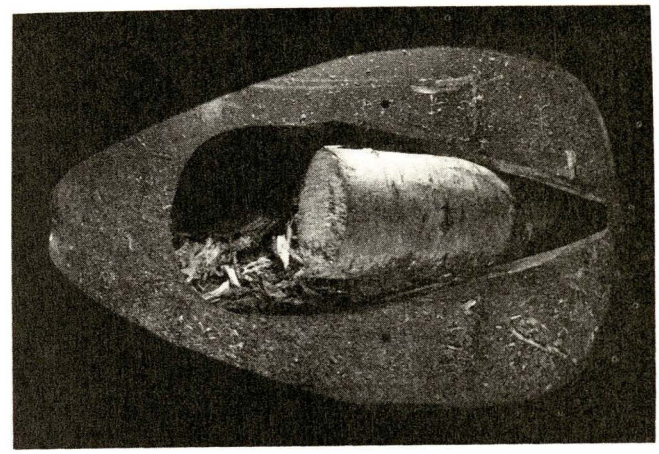


Figure 5.—*Teardrop-shaped cutter opening on the Teardrop Chunker.*

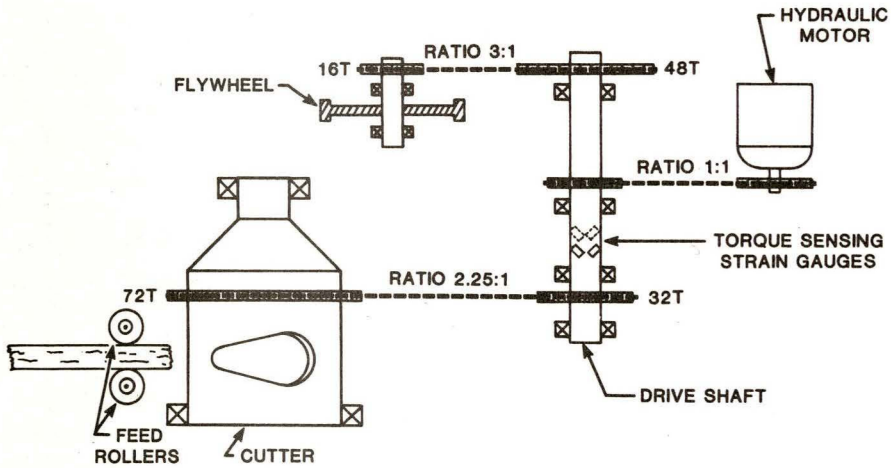


Figure 4.—*Schematic of Teardrop Chunker drive train.*

the rotational speeds of both the cutter drum and infeed rollers. The drum is 14-1/2 inches high, 16 inches in diameter, and 1/4 inch thick. The teardrop hole openings are 18 inches long; they are 7 inches wide at the large end and taper down to 3/4 inch wide at the small end. The cutting edge is a single bevel formed by removing the inside edge of the teardrop opening in the drum.

To assist in the cutting action, a 17-inch-diameter, 2-inch-thick flywheel is used. The drum, flywheel, and a hydraulic motor are all tied to a common drive shaft by means of individual chain and sprocket arrangements. Because of the sprocket ratios used, the common drive shaft and hydraulic motor rotate 2.25 times faster than the cutter drum, and the flywheel rotates 6.75 times faster than the cutter drum.

The feed mechanism consists of four rollers (two above the log and two below) that grip and propel the log into the rotating cutter openings. Each feed roller tapers from 8 inches in diameter on the ends to 6 inches in diameter in the middle.

PROCEDURES

The machine was tested using two species of wood and two nominal chunk lengths. The species tested were aspen, a low-density hardwood, and sugar maple, a high-density hard-

wood. The two chunk lengths chosen were short, from 3 to 4 inches long in the fiber direction (our unofficial standard), and long, the maximum length of chunk the machine would produce.

A small number of trial runs were made to determine a suitable combination of cutter and feed roller speeds. The cutter and feed settings selected were as follows:

	Short chunks	Long chunks
Cutter speed (rpm)	147	118
Feed roller speed (rpm)	175	254

The test logs were green, 8 feet long, delimbed, straight, and free of large knots. Their average diameters ranged from 3.2 to 5.4 inches. Each test log was weighed and measured for both small and large end diameters and length. From these data we calculated initial log volumes (using the truncated cone approximation), average log diameter, and average log density. The logs were fed into the machine large end first. To eliminate the problem of uncontrolled cutting that occurs after the end of the log leaves the feed mechanism, the feed was stopped before the end of the log passed through. Therefore, about 2 feet of the log was not chunked for each test. The weight of this residual piece was subtracted from the initial log weight to determine the net weight chunked. The net volume of log chunked was calculated by dividing the net weight chunked by the average log density.

For each test log we determined the average length of the chunks produced. The log was marked with five different colored bands located 16 inches apart. Five chunks, one from each colored band, were collected and analyzed for average length. The chunks had irregularly shaped ends so we measured both the minimum and maximum length and then determined the mean.

Because of the exploratory nature of the study, we did not randomize the testing. The short chunk tests were conducted first. The species were alternated between consecutive tests.

After the testing was completed, we weighed the total output for each of the four different chunk types in 4.6-cubic foot batches (30-gallon garbage can) and calculated the mean bulk densities. We also took material samples of each chunk type and analyzed them for particle size distribution and moisture content.

The four chunk types produced—aspen and sugar maple, short and long—were characterized by screening for size and analyzing each size fraction for average particle weight. Samples of each chunk type were manually classified using a plywood board with a series of round holes. The holes ranged from 1/2 inch to 3-1/2 inches in diameter in 1-inch increments. Each sample was sorted into groups based on the smallest hole size that would pass the piece.

To further define machine performance, we analyzed chunk length, productivity, torque, power, and energy factors. A two-way analysis of variance (ANOVA) was made to determine what effect the independent variables, species and nominal chunk length, had on average chunk length, rate of production, peak torque, average torque, average horsepower, and average energy. The data were combined where there were no significant differences at the 0.01 level and plotted against average log diameter. Linear regression equations were developed for those plots where the linear correlation coefficients were statistically significant at the 0.01 level.

INSTRUMENTATION

A recording oscillograph (Consolidated Electrodynamics Corporation Model 5-124A[3]) was used to record drive shaft cutting torque, integrated drive shaft cutting torque, and cutting drum rotation signals. The drive shaft cutting torque was measured using a four-active arm Wheatstone bridge circuit. The bridge circuit consisted of four strain gauges mounted circumferentially

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others that may be suitable.*

around the shaft with the gauge elements oriented 45 degrees to the shaft center line. The gauged shaft was statically calibrated for torque by locking the center section of the shaft in a special fixture and twisting the gauged section by means of a lever arm and hydraulic cylinder mounted in place of the corresponding drive sprocket and chain. A load cell was placed in series with the hydraulic cylinder to measure the force applied.

Cutter drum rotation was sensed by an electromagnetic pickup that produced one pulse per drum revolution. The average cutter drum revolutions per minute (rpm) were calculated by dividing the number of revolutions made during the cutting by the time taken. Average drive shaft rpm was calculated by multiplying the drum rpm by 2.25, the sprocket ratio.

For each test, we determined peak cutter drive shaft torque, average cutter drive shaft torque, average power, and average energy transmitted to the cutter. Average cutter drive shaft torque was determined by electronically integrating the instantaneous torque signal and then dividing the integral by the cutting time. Average power transmitted to the cutter was calculated using the average torque and the average drive shaft rpm. Average energy was calculated by dividing the average power by the production rate.

TEST RESULTS

Of the 32 logs chunked, 20 (10 aspen and 10 sugar maple) were made into short chunks, and 12 (8 aspen and 4 sugar maple) were made into long chunks. The average diameter of the aspen logs ranged from 3.3 to 5.4 inches; the average diameter of the sugar maple logs ranged from 3.3 to 4.5 inches. Although the machine successfully cut a 4.5-inch-average diameter (4.8-inch-maximum diameter) sugar maple log while set to produce short chunks, it stalled on a 4.5-inch-average diameter (4.9-inch-maximum diameter) sugar maple log while set to produce long chunks.

The Teardrop Chunker produced mainly large chunks of wood, which were primarily solid, unfractured, short sections of log (fig. 3). At least 75 percent of the weight of each sample was composed of particles larger than 3-1/2 inches in diameter (table 1). An intermediate amount (from 6 to 21 percent by weight) of smaller chunks passed through a 3-1/2-inch round hole but not through a 1-1/2-inch round hole. A small amount (from 4 to 7 percent by weight) of particles and fines, primarily bark and surface fiber torn off by the feed rolls, passed through a 1-1/2-inch round hole.

Both the short and long chunks of aspen had a bulk density of 23.7 pounds/cubic foot (lb/cu ft) at an average moisture content of 52 percent (wet-weight basis). The bulk density for sugar maple ranged from 27.5 lb/cu ft for short chunks to 29.3 lb/cu ft for long chunks at an average moisture content of 37 percent.

The average chunk length produced for the various log diameters chunked ranged from 2.8 to 4.9 inches for short chunks and from 4.5 to 7.2 inches for long chunks (fig. 6). The two species were combined because the two-way ANOVA indicated that there was no significant difference between species data at the 0.01 level. Linear regression equations were developed, because both the short and long chunk groups had significant negative linear correlation coefficients at the 0.01 level (table 2).

The average rate of production ranged from 6.9 to 10.9 cubic feet/minute (cu ft/min) for short chunks and from 7.8 to 13.4 cu ft/min for long chunks (fig. 7). Again, the aspen and sugar maple data were combined because the ANOVA test indicated that there was no significant difference between them. The linear correlation coefficients indicate a significant positive linear correlation between production rate and log diameter (table 2).

The average torque and peak torque developed in the cutter drive shaft are shown plotted in figure 8. Here, the data for the two nominal chunk lengths were combined because there was no statistical difference between them. Average torque of the cutter drive shaft ranged from 154 to 409 foot-pounds for aspen and from 281 to 583 foot-pounds for sugar maple. Peak torque ranged from 869 to 2,020 foot-pounds for aspen and from 1,928 to 3,156 foot-pounds for sugar maple. (Note: A peak torque of 3,400 foot-

Table 1.—*Screen retention fractions and particle weight statistics*

Screen size range (inches)	Percent of total weight[1]	Mean particle weight[1]	Range
		- - - Grams - - -	
		Aspen short chunks	
<0.5	3	-	-
0.5-1.5	4	0.7	0-17
1.5-2.5	2	14.1	2-63
2.5-3.5	17	113.0	25-288
>3.5	75	261.5	52-485
		Aspen long chunks	
<0.5	4	-	-
0.5-1.5	3	0.7	0-11
1.5-2.5	1	10.5	1-35
2.5-3.5	7	105.4	29-330
>3.5	85	432.8	84-633
		Sugar maple short chunks	
<0.5	4	-	-
0.5-1.5	3	0.9	0-14
1.5-2.5	1	11.1	3-26
2.5-3.5	5	223.5	76-370
>3.5	88	441.9	45-675
		Sugar maple long chunks	
<0.5	3	-	-
0.5-1.5	1	0.7	0-4
1.5-2.5	0	20.0	7-33
2.5-3.5	21	369.2	74-693
>3.5	75	723.6	542-953

[1]Oven-dry weights.

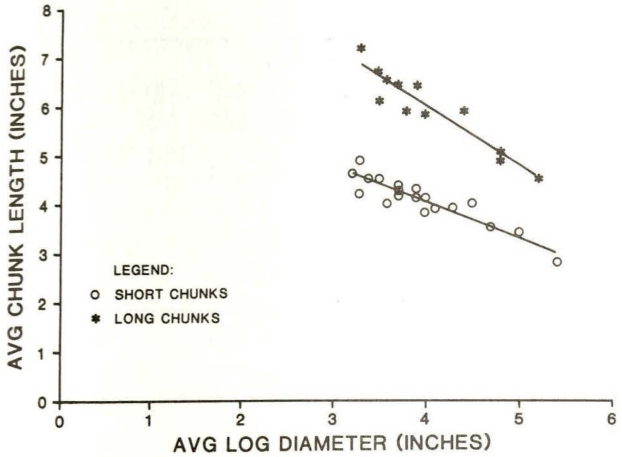


Figure 6.—*Test data and the linear regression lines for average chunk lengths produced for short and long chunk production settings.*

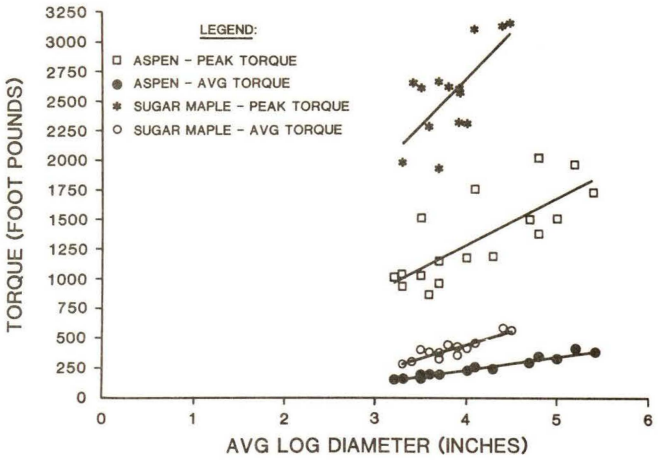


Figure 8.—*Test data and the linear regression lines for aspen and sugar maple peak and average torque.*

pounds was recorded when the cutter stuck while attempting to cut the 4.5-inch sugar maple mentioned above.) The linear correlation coefficients show significant positive linear correlations between torque and log diameter (table 2).

The average power transmitted to the cutter by the drive shaft ranged from 9.7 to 23.2 horsepower for aspen and from 17.5 to 33.1 for sugar maple (fig. 9). The short and long chunk length data were combined because there was no significant difference between them. The linear correlation coefficients indicate significant positive linear correlations between power required and log diameter (table 2).

The average energy transmitted to the cutter as it relates to the various log diameters tested is shown in figures 10 and 11. Species and nominal chunk length factors are presented separately because they were found to be significant. For aspen, energy ranged from 1.3 to 2.1 horsepower-minutes/cubic foot (hp-min/cu ft) for short chunks and from 1.0 to 1.5 hp-min/cu ft

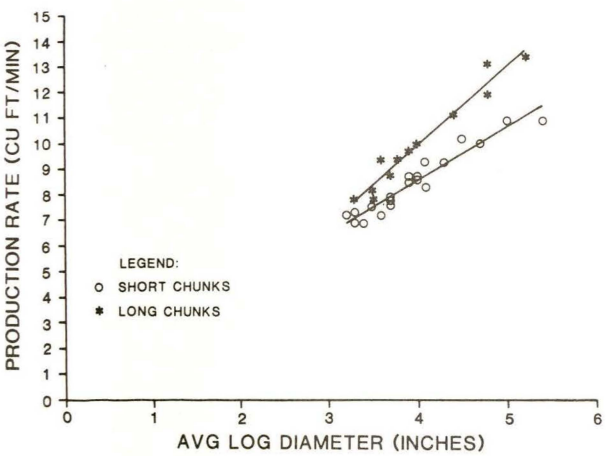


Figure 7.—*Test data and the linear regression lines for production rates developed producing short and long chunks.*

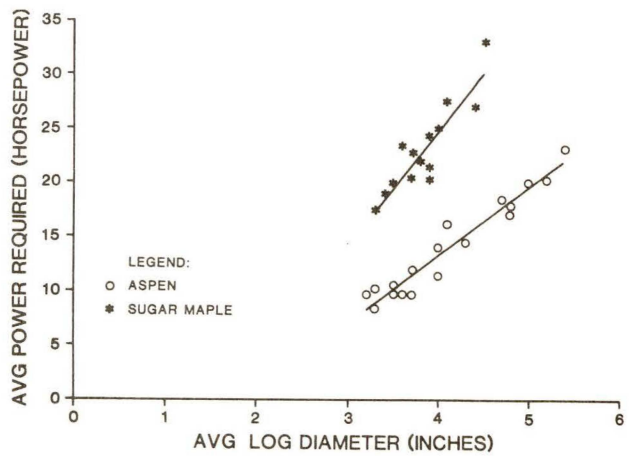


Figure 9.—*Test data and the linear regression lines for average power required to produce aspen and sugar maple chunks.*

Table 2.—*Teardrop chunker performance*

	Regression equation	Linear correlation coefficient R	Significant at 0.01 level
Chunk length			
Short chunks	Length (inches) = 6.95 - .73 x avg. diameter (inches)	- 0.91	Yes
Long chunks	Length (inches) = 10.88 - 1.22 x avg. diameter (inches)	- .94	Yes
Productivity			
Short chunks	Production (cu ft/min) = 0.16 + 2.10 x avg. diameter (inches)	.96	Yes
Long chunks	Production (cu ft/min) = -2.46 + 3.09 x avg. diameter (inches)	.98	Yes
Peak torque			
Aspen	Peak torque (ft-lb) = -294.15 + 394.96 x avg. diameter (inches)	.77	Yes
Sugar maple	Peak torque (ft-lb) = -434.75 + 780.46 x avg. diameter (inches)	.69	Yes
Average torque			
Aspen	Avg. torque (ft-lb) = -221.64 + 114.00 x avg. diameter (inches)	.97	Yes
Sugar maple	Avg. torque (ft-lb) = -441.07 + 220.87 x avg. diameter (inches)	.89	Yes
Power			
Aspen	Power (horsepower) = -11.75 + 6.27 x avg. diameter (inches)	.97	Yes
Sugar maple	Power (horsepower) = -17.36 + 10.57 x avg. diameter (inches)	.89	Yes
Energy			
Aspen			
Short chunks	Energy (horsepower-min/cu ft) = .32 + .32 x avg. diameter	.95	Yes
Long chunks	Energy (horsepower-min/cu ft) = .25 + .24 x avg. diameter	.94	Yes
Sugar maple			
Short chunks	No significant linear correlation	.59	No
Long chunks	No significant linear correlation	-.15	No

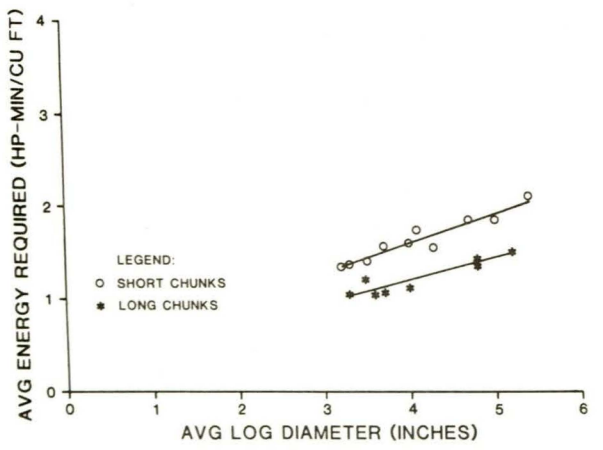


Figure 10.—*Test data and the linear regression lines for average energy required to produce aspen short and long chunks.*

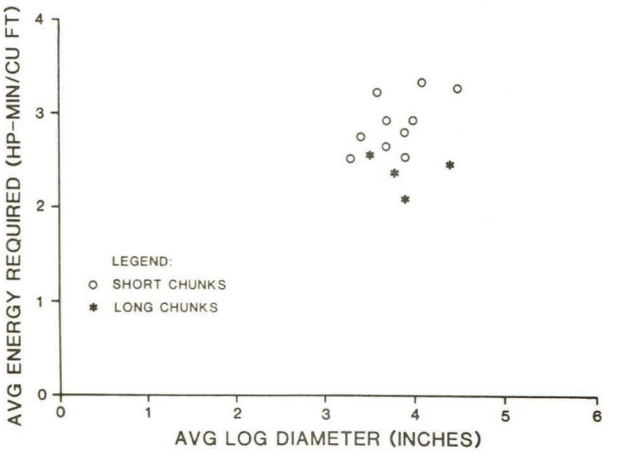


Figure 11.—*Average energy required to produce sugar maple short and long chunks.*

for long chunks (fig. 10). Sugar maple energy ranged from 2.5 to 3.3 hp-min/cu ft for short chunks and from 2.1 to 2.6 hp-min/cu ft for long chunks. The aspen data show significant positive linear correlations between energy and log diameter. However, because the sugar maple linear correlation factors were not found to be significant at the 0.01 level, the linear regression equations and lines were not determined. The small number of data points made it impossible to explain the scatter in the sugar maple data.

CONCLUSIONS AND RECOMMENDATIONS

The Teardrop Chunker successfully produced short, round, intact chunkwood sections from both aspen and sugar maple logs. Short and long chunks were made from the two species.

Species did not significantly affect actual average chunk length or production rate; nominal chunk length did not significantly affect torque or power. However, energy was significantly affected by both. Over the range tested, average log diameter had a linear effect on chunk length, productivity, power, and energy. However, because the range of log diameters and the number of data points are limited, the linear regression equations should be used with care, and extrapolation should be avoided.

Although the Teardrop Chunker's maximum size limit was not established for aspen, it appears to be less than 5 inches in diameter (maximum) for sugar maple, especially when producing long chunks where the rotational speeds and thus the kinetic energy stored in the drum and flywheel are reduced.

The Teardrop Chunker is a laboratory prototype built to test the teardrop cutter concept. Commercial application would require further engineering and testing based on the data we have developed. We believe that the Teardrop Chunker's small size, simple design, and low horsepower requirements make it a good candidate for a tractor-mounted, three-point-hitch attachment. Such an attachment could be used to process low-valued, small-diameter woodlot thinnings into chunks of wood suitable for small-scale, hand-fired combustors often found in residences, farms, and small industries.

Metric Conversions

1 cubic foot = 0.0283 cubic meter
1 cubic foot/minute = 0.00047 cubic meter/second
1 foot = 0.3048 meter
1 foot/minute = 0.0051 meter/second
1 foot-pound = 1.3558 newton-meters
1 horsepower = 746 watts
1 horsepower-minute/cubic foot = 1,580 kilowatt-hours/cubic meter
1 inch = 2.54 centimeters
1 pound = 0.4536 kilogram
1 pound/cubic foot = 16.02 kilograms/cubic meter
1 square foot = 0.0929 square meter

Literature Cited

Arola, Rodger A.; Sturos, Joseph B. 1982. **A portable chunking machine**. Res. Note WO-11. Washington, DC: U.S. Department of Agriculture, Forest Service. 4 p.

Arola, Rodger A.; Radcliffe, Robert C.; Winsauer, Sharon A.; Matson, Edsel D. 1982. **A new machine for producing chunkwood**. Res. Pap. NC-211. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 8 p.

Barwise, Robert D.; Arola, Rodger A.; Erickson, John R., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1977. **Helical head comminuting shear**. U.S. patent 4,053,004. October 11. Int. Cl.[2] B27C 1/08. U.S. Cl. 144/162 R. 10 p.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. **Involuted disc slicer**. U.S. patent 4,431,039. February 14. Int. Cl.[3] B27L 11/02. U.S. Cl. 144/176. 11 p.

Kangas, Vernon W.; Kangas, Roy J.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1986. **Multi-product wood processor**. U.S. patent 4,607,672. August 26. Int. Cl.[4] B27C 9/00. U.S. Cl. 144/2 R. 9 p.

Total-Tree Chunkwood as Raw Material for Flake Products[1]

Bruce A. Haataja, Roy D. Adams, and Rodger A. Arola[2]

Abstract.—This study evaluated the technical and economic suitability of flakes made from chunked aspen and red maple wood produced by the USDA Forest Service "chunking machine" as furnish for flakeboard, oriented strandboard, and highly aligned products. Results indicated that structural panels can be produced with acceptable strength and physical properties. Analysis indicated that net raw material cost savings are possible with the chunkwood system.

INTRODUCTION

Structural flakeboards rely on engineered, high-quality, bark-free flakes in developing their superior strength properties at low resin levels and medium densities. This is true for both random and oriented strandboards. For the most part, the flakes for these products are made from peeled logs or pulpwood bolts. The logs are directly converted with disk-, drum-, or lathe-type flakers to produce the quality of flakes needed.

An alternate system for producing flakes is from forest residue and total-tree material, which recovers one and one-half to two times as much wood per acre as conventional logging. Total-tree harvesting is becoming more prevalent as a system for recovering wood for fuel, pulp and paper, fiberboard, and particleboard. Forest residue and total-tree material can be converted to flakes by first reducing it to chunks (chips that are 2 to 4-1/2 inches long), processing the chunks into fingerlings (particles that are 2 to 4-1/2 inches long by about 3/4 inch in cross section), and then flaking in a ring flaker (Heebink 1972).

The key element in this process has been the system for producing the fingerling of proper geometry. Researchers (Erickson 1976, Gardner *et al.* 1978, Heebink and Dominick 1971) have reported that high-quality flakes can be made from total-tree material in a ring-type flaker if the material were first reduced to a fingerling-size particle. In general, these researchers have noted that although disk flakes produce panels with improved properties, ring-flaked panels can exceed Canadian and American standards. In 1972 Heebink (1972) presented a challenge to the designers of chipping equipment to develop a machine to produce fingerlings.

---

[1]*Paper presented at the symposium of the Council on Forest Engineering and International Union of Forestry Research Organizations - 1984. [University of Maine, Orono, and University of New Brunswick, Fredericton, Canada, August 11-18, 1984.]*

[2]*Bruce A. Haataja is Senior Research Scientist, Institute of Wood Research, Michigan Technological University, Houghton, Michigan; Roy D. Adams is Associate Director for Bio Products, Natural Resources Research Institute, University of Minnesota, Duluth, Minnesota, formerly Senior Research Scientist, Institute of Wood Research, Michigan Technological University, Houghton, Michigan; and Rodger A. Arola is Research Mechanical Engineer, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

The size and geometry of fingerlings are important for several reasons. The length of the fingerling controls the upper limit of flake length. It is necessary that flake length be substantially 2 inches or greater for structural flakeboard; therefore the fingerling should be 2 inches or greater in length. Because ring flakes rely on centrifugal forces to position the fingerling's long dimension parallel to the cutting edge of the knife, the fingerling should have about a 4 to 1 length-to-thickness ratio to ensure a proper positioning with the knife. Fingerlings that are long enough but too thick in cross section often plug the inlet to the ring flaker. Further, the cross section of the fingerling controls flake width. For oriented strandboard it is important to have long, narrow strands rather than wide wafers.

The studies referred to indicate the need for equipment to produce a high-quality fingerling. In addition to the drum chipper used by Heebink *et al.* (1977), other machines have been developed to produce large chips and fingerlings. Erickson (1976) reported on a spiral-head chipper developed by the USDA Forest Service, Forestry Sciences Laboratory, at Houghton, Michigan. This machine produced chips or blocks about 2-1/2 inches long. When fed through a hammermill, the chips broke down into fingerlings. Panels made from these ring-flaked fingerlings had good properties. Recently, the Forestry Sciences Laboratory at Houghton has developed a chunking machine reported by Arola *et al.* (1983) that produces chunks from 2 to 4-1/2 inches long with cross sections often equalling the entire tree cross section. The chunks usually have longitudinal fractures that help in the subsequent breakdown of the chunks into fingerlings. The Institute of Wood Research (IWR) at Michigan Technological University at Houghton, Michigan, developed a prototype chunk splitting machine that is capable of reducing chunks into fingerlings while retaining the original chunk length. With these two machines, fingerlings 2 to 4-1/2 inches in length by about 3/4 inch in cross section were produced.

A technology for producing a high-strength composite wood material (CWM) from elongated wood flakes has been developed at the Institute of Wood Research. Structural products, such as utility poles and crossarms, have been manufactured from CWM and are undergoing service testing. The CWM technology currently uses species that would not usually be found as structural products. Although this material requires an engineered flake; i.e., size is restricted to fairly close tolerances, it is anticipated that these flakes could be produced from small trees and residue material, providing that suitable production equipment is available.

Under contract with the USDA Forest Service, the Institute of Wood Research conducted two research studies involving chunkwood. The objectives of the studies were to evaluate the technical and economic suitability of flakes produced from chunkwood as furnish for flakeboard products. A particular objective of the second study was to determine the way in which board density and strength properties were affected by combining dense hardwood and aspen flakes.

The purpose of this paper is to describe the laboratory methods and equipment used to process bolts into high-quality flakes using the chunkwood concept and to relate this to a commercial situation. A flow diagram outlining project steps is shown in figure 1.

MACHINE DESCRIPTIONS

USDA Forest Service Chunker

The USDA Forest Service wood chunker was specifically designed for controlled laboratory testing to reduce roundwood bolts up to about 9 inches in diameter into chunks (fig. 2). The flywheel and carrier for the cutting blades was a 1-3/4-inch-thick, 3-foot-diameter steel disk. The disk was mounted on a horizontal shaft running in a pair of bearings secured to a rigid frame. A diagram of the chunker is shown in figure 3.

Three curved, 24-inch-long, detachable blades, bent on an 18-inch radius, were mounted 120 degrees apart and positioned on the face of the disk so that the curved plane was at right angles to the axis of the workpiece. The leading edge of each blade was set at a greater radial distance from the center of shafting than the trailing edge.

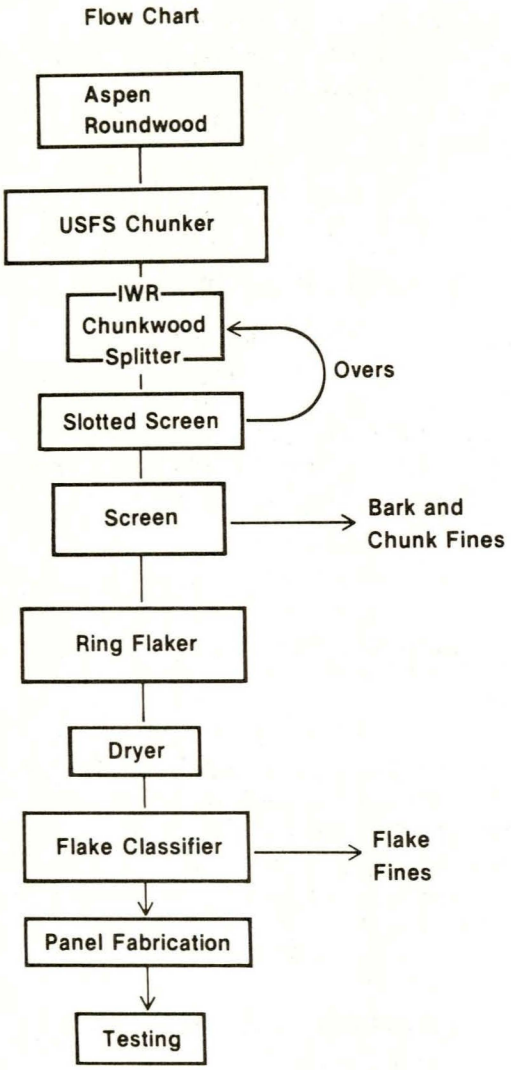


Figure 1.—*Flow diagram for project.*

The blades were tapered so that the leading edge projected about 1 inch from the face of the disk, whereas the trailing edge projected about 9 inches (equivalent to the maximum diameter of cut). Two sets of blades for testing were fabricated—1/4 inch and 3/8 inch thick—both with a 30-degree included angle double bevel.

The workpiece was fed through a tubular anvil made from a 9-1/2-inch-diameter pipe horizontally secured to the infeed frame. The anvil tube was located near the rim of the disk, but offset from the plane of the disk, so that it was aligned with the cutting blades. The center of the anvil tube was positioned slightly below the disk

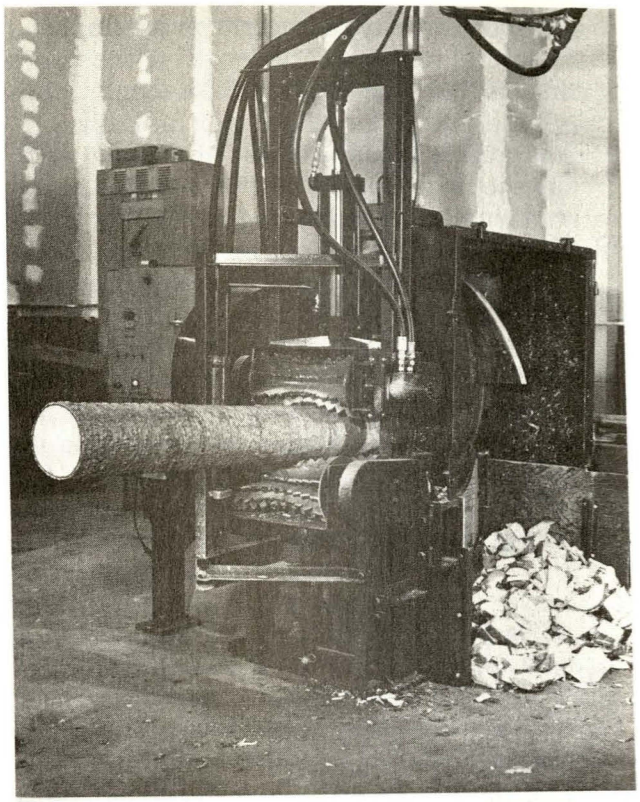


Figure 2.—*USDA Forest Service chunker.*

center to obtain the desired entry and exit of the blades. The anvil tube was contoured to provide slight clearance between it and the blades as the chunks are severed from the workpiece.

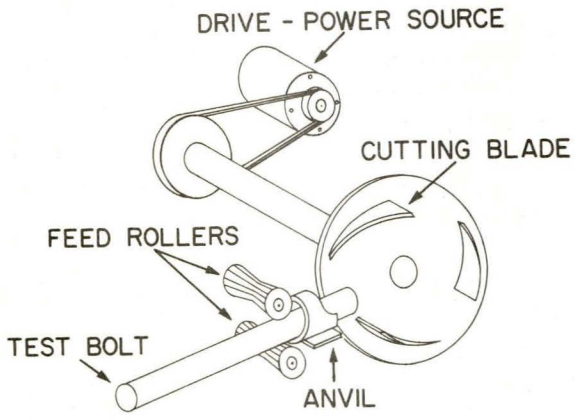


Figure 3.—*Diagram of USDA Forest Service chunker.*

Because the workpiece does not self-feed, a pair of hydraulically powered rollers was positioned immediately ahead of the anvil. The speed of the feed rolls was adjustable. To accommodate test bolts of different diameters, an air-operated cylinder was used to lift the upper roll to insert the bolt and to exert a downward force on the workpiece during test.

A 175-horsepower diesel engine provided power to operate the chunking machine. The disk was driven through a speed reducer and sprocket/roller chain drive system. The rotational speed of the cutter disk was variable.

IWR Chunkwood Splitter

When long wood chunks (i.e., 2 to 4 inches long) are produced, they usually have large transverse sections and may be as large as the cross section of the tree stem being chunked. Usually some longitudinal splitting occurs, but chunks remain large enough in cross section to cause flow problems through a ring flaker. Large cross-section chunks also produce wider flakes than what is desired for flake alignment processes. Wide flakes can be reduced in width by subsequent operations but generally at the expense of additional "fines."

The IWR chunkwood splitter is based on a concept for splitting large chunks into fingerlings without producing an excessive amount of "fines" or damaging the chunks in ways that would produce excessive fines in subsequent flaking. The basic tool or bit employed by this concept is a hardened steel cone with a relatively sharp point. Splitting is caused by impaling the chunk with the cone-shaped bit. The chunk may be pierced at any possible grain orientation. This will cause splitting along the grain. With a sharp point on the bit, no cutting and little crushing of the wood fiber occurs.

Although several machine designs are possible, the IWR laboratory model chunk splitting machine was made using a jaw mounted with impaling bits. Figure 4 shows a sketch of the arrangement of jaw mounted with impaling bits, cleaner plate, and bedplate. A photograph of the laboratory machine is shown in figure 5. The features of this machine include the following:

1. A hinged impaling head so that it works like a jaw with the bedplate.
2. A cleaner plate is included so that any chunks that stick to the impalers are wiped off when the head rises.
3. A hydraulic cylinder which actuates the impaling head.
4. More numerous and smaller diameter impalers further into the throat of the machine to provide increasing chances of additional splitting as the chunks move through the machine.
5. Impalers of simple configuration.
6. A sloped bedplate to allow gravity flow of material through the machine.
7. A gate at the lower end of the bedplate (not shown) which controls the flow through the machine when the jaws are open.

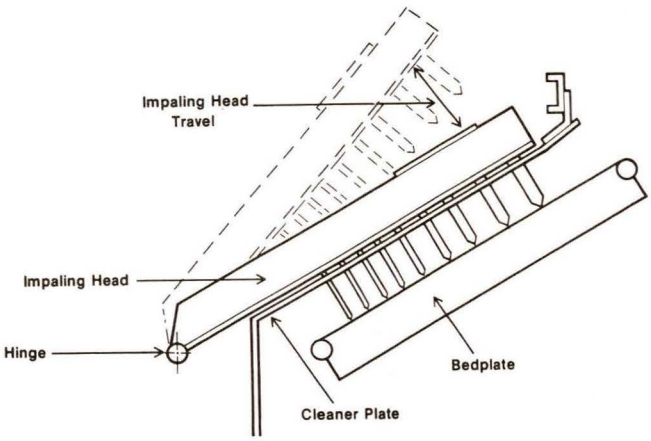


Figure 4.—*Section view of impaling head, bedplate, and cleaner plate.*

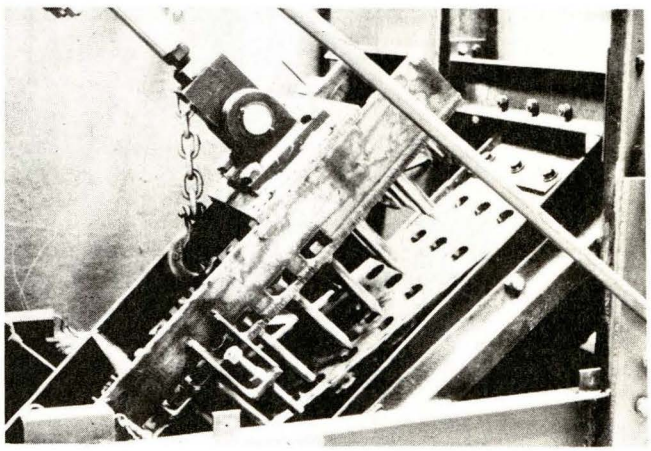


Figure 5.—*Chunkwood splitter from the Institute of Wood Research at Michigan Technological University.*

This laboratory chunk splitting machine successfully reduced large wood chunks produced by the Forest Service wood chunker into fingerlings that passed through a 3/4-inch slotted screen.

FLAKE AND PANEL PRODUCTION

General Observations

Log quality was limited to sound logs and to a size that maximized the capacity of the "chunking machine"; i.e., about 8-1/2 inches in diameter. Sample bolts were reduced to 2- to 4-inch-long chunks on the Forest Service chunking machine. The aspen chunks shown in figure 6 were too large for ring flaking and were subsequently reduced to fingerlings of 3/4-inch cross section in the prototype chunkwood splitter. A 3/4-inch rotary slotted screen was used to accept only those particles meeting the required cross section. All oversize material was recycled through the chunkwood splitter until acceptable in size. Figure 6 also shows some typical aspen fingerlings.

The accepted fingerlings were flaked using a Black Clawson MKZ-14 ring flaker[3] at the Institute of Wood Research. The flaker knives were set to produce a nominal flake thickness of 0.020 inch, and a sample of 50 flakes randomly selected averaged 0.020 inch in thickness. The length of the flakes was determined by the length of fingerlings which ranged from 2 to 4-1/2 inches. Example flakes are also shown in figure 6. The flakes were dried to 5-percent moisture content. Three flake classifications were then obtained; i.e., those retained by 1/8-, 1/4-, and 1/2-inch screens, referred to as +1/8, +1/4, and +1/2, respectively. These screen sizes approximately determine the minimum flake width retained.

---

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the Michigan Technological University or the United States Department of Agriculture to the exclusion of others that may be suitable.*

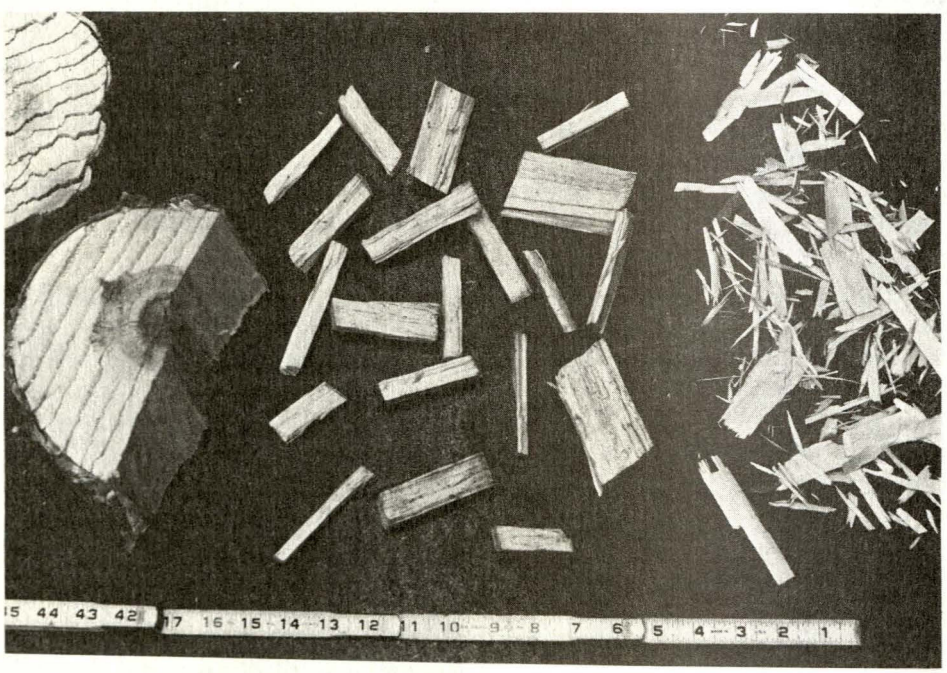


Figure 6.—*Aspen chunks produced by the USDA Forest Service involuted disk chunking machine, fingerlings that were split from chunks in the Institute of Wood Research prototype chunkwood splitter, and ring flakes made from the fingerlings.*

Study No. 1

Sixteen panels 1/2 by 16 by 96 inches were fabricated at a nominal density of 42 pounds per cubic foot (pcf). Panel differences were based on flake classification and adhesive type/level. The adhesive type/level was related to the flake orientation method used. A 5-percent level of phenol-formaldehyde was used for random and oriented strandboard panels, and an 8-percent level of isocyanate was used in the highly aligned panels. The resin and flake classification choices were based on those used in commercial and experimental panels that were used for strength comparisons. The press temperature was 330 degrees F, and press closing was achieved in 1 to 2 minutes. The press time for the phenol-formaldehyde adhesive was 20 minutes; it was 15 minutes for isocyanate adhesive.

Study No. 2

In this work a dense hardwood species—red maple—was selected to be combined with aspen in the production of panels. Red maple was chosen because it is overabundant in the Lake States, often has poor form on "off" sites and is frequently unsuited for sawmilling, and grows thickly on good sites, allowing substantial thinning volume. Also, its texture and density are similar to paper birch, suggesting that similar results might be achieved with paper birch.

For Study No. 2, ring flakes were produced from chunkwood manufactured from aspen and red maple bolts in the same manner as Study No. 1. The flakes used for test panel production were those retained on a 1/4-inch screen. Ninety panels 1/2 by 18 by 18 inches were fabricated at a target density of 42 pcf. As in Study No. 1, all random and oriented strandboard panels were blended with 5-percent liquid phenol resin. The highly aligned material was blended with 8-percent isocyanate adhesive. Other than board type, variables included the ratio of aspen to red maple flakes and homogeneous mixtures versus layering. Layering was accomplished by using one-half of the total aspen component for a particular panel on each surface, and red maple was used for the cores. The press temperature was 350 degrees F, and press closing was achieved in 1 to 2 minutes. The press time was 12 minutes.

PANEL PROPERTIES AND DISCUSSION

Average values for bending strength (MOR), bending stiffness (MOE), material density, and internal bond (IB) are given in table 1 for the two studies. Data are given for random oriented panels, oriented strandboard (OSB), and highly aligned material (HAM); in addition minimum values required by Commercial Standard CS 236-66 (U.S. Department of Commerce 1966), Forest Service Targets (Erickson 1976), and data from a study by Price (1977) are presented. The MOR and MOE averages for the aligned material (i.e., OSB and HAM) are given parallel to the flake orientation.

As one would expect, material density influences strength. Regression analyses were performed using the individual data points. We found that as the panel properties increased, the density effects became more marked, so that a change in density of the highly aligned material has far more influence on properties than for the random panels.

The results of the two studies were comparable even though combinations of aspen and red maple were used in Study No. 2. Data for the 50:50 mix are presented. In Study No. 2 the various aspen to red maple ratios and homogeneous versus layered panel configuration appeared to have little effect on bending characteristics. The influence of flake classification in Study No. 1 was minimal and inconsistent; therefore results are combined in the average values presented. The effect of flake orientation on bending properties is seen when comparing the random and OSB panels that were made with the same liquid phenol-formaldehyde adhesive levels. The use of higher levels of isocyanate adhesive and a greater degree of orientation are seen in the high bending strength results for the highly aligned material.

The purpose of Commercial Standard CS 236-66 is to establish a voluntary standard of quality for particleboard and is intended to provide minimum property values. Those listed are for medium density material bonded with a durable adhesive and therefore are suitable for certain exterior applications. The Forest Service Target values shown were developed for flakeboard, so that flakeboards meeting these goals should perform satisfactorily in structural applications.

Table 1.—*Comparison of test results, commercial standard, target values, and published flakeboard properties*

Source	Property			
	Modulus of Rupture	Modulus of Elasticity	Density	Internal bond
	psi	*psi x 10^3*	*pcf*	*psi*
Test results				
Study No. 1				
Random panels	4,265	705	41.9	43.0
OSB-aspen[1]	8,145	1,365	45.9	78.3
HAM-aspen[2]	11,680	1,810	41.0	221.2
Study No. 2				
Random panels	5,605	730	44.8	83.4
OSB-50:50 aspen/maple mix	7,610	1,195	40.9	65.6
HAM-all mixes	12,737	1,770	42.3	301.8
Commercial Standard CS 236-66[3]	2,500	450	37 to 50	60
Forest Service Targets	4,500	800	37 to 43	70
Published study				
Random panels	5,300	800	47.5	83
Oriented panels	6,600	1,090	45.5	82

[1]OSB = oriented strandboard.
[2]HAM = highly aligned material.
[3]U.S. Department of Commerce 1966.

Observation of the bending strength values in the two studies involving material made from ring flakes indicates properties much greater than the minimums given in CS-236. Except for the random panels in Study No. 1, MOR values exceed the Forest Service Targets and results achieved by Price (1977) using hardwood mixtures. MOE values of random panels were somewhat lower, but manipulation of density and/or manufacturing techniques cculd increase the results.

The effect of the fairly high levels of isocyanate adhesive on internal bond strength can be seen in table 1 which shows very high values for the highly aligned material. Internal bond values using the phenol-formaldehyde were low; however in most cases they approached or exceeded the values in CS-236 and the Forest Service Target values. Again, manipulation of density and production techniques should improve these values.

The results presented indicate that it is feasible to produce structural panels using ring flakes obtained from chunked wood using either aspen or aspen:red maple combinations. Although strength properties of the highly aligned material were somewhat lower than those recorded for material produced from drum-type flakes, the bending strength properties were exceptional; thus material produced from ring flakes has application in the IWR composite wood products.

Other hardwood species of the Lake States should be considered for furnish for composite products. Based on the results of this study, it is likely that paper birch and American elm could be substituted for red maple because of density similarities. Other hardwoods such as red oak, sugar maple, yellow birch, and American beech are also potential species. Substantial volumes of all of these species are available in chunkable form, such as small-diameter, low-grade trees; logging residue; and thinnings.

PRELIMINARY COST COMPARISON

Estimates (in 1984) were made of the cost of producing flakes from roundwood and from chunks. These are shown in the following tabulations which indicate the cost of producing 1 ton (oven-dry basis) of +1/4- and +1/8-inch classification flakes from each system, respectively. Because fewer trees are needed to produce a given quantity of flakes from chunks than roundwood, the cost of stumpage and harvesting wood for chunking is less. Also, the procurement radius for chunks would be less than for roundwood, resulting in lower trucking costs.

Cost of producing roundwood flakes from 1 ton of standing timber (O.D. basis)

1. Stumpage - 0.57 cord (1 ton) @ $5.00	$ 2.85
2. Procurement fee - 0.57 cord @ $2.50	1.43
3. Harvesting - 0.57 cord @ $19.00	10.83
4. Haul - 0.57 cord @ $15.00 (50 miles)	8.55
5. Yard - 0.57 cord @ $5.00	2.85
6. Thaw - 0.57 cord @ $4.33	2.47
7. Debark - 0.57 cord @ $12.00	6.84
8. Flake - 0.485 cord @ $9.51	4.61
9. Dry - 0.485 cord @ $17.76	8.61
10. Classify - 0.485 cord @ $1.06	.51
Total	$49.55

Cost per ton of +1/4-inch classification flakes = $\frac{\$49.55}{.403 \text{ ton}}$ = $122.95

Cost per ton of +1/8-inch classification flakes = $\frac{\$49.55}{.415 \text{ ton}}$ = $119.40

Cost of producing ring flakes from 1 ton of standing timber (O.D. basis)

1. Stumpage - 1 ton (0.57 merchantable cord @ $5.00)	$ 2.85
2. Procurement fee - 1 ton @ $2.06	2.06
3. Harvesting - 1 ton (0.57 merchantable cord @ $18.00)	10.26
4. Chunk - 1 ton @ $10.00	10.00
5. Haul - 1 ton @ $9.00 (40 miles)	9.00
6. Yard - 1 ton @ $4.45	4.45
7. Chunk splitting - 1 ton @ $5.00	5.00
8. Thaw - .949 ton @ $3.85	3.65
9. Flake - .949 ton @ $8.44	8.01
10. Dry - .949 ton @ $17.76	16.85
11. Classify - .949 ton @ $1.06	1.01
Total	$73.14

Cost per ton of +1/4-inch classification flakes = $\frac{\$73.14}{.647 \text{ ton}}$ = $113.04

Cost per ton of +1/8-inch classification flakes = $\frac{\$73.14}{.767 \text{ ton}}$ = $95.35

The net cost differences are dependent on the classification of flakes desired after screening. The chunkwood system recovers the greatest volume of wood from each tree, and the roundwood system recovers the most from the material actually brought to the mill when a +1/4-inch flake classification is sought. This balances out some of the previously mentioned gains from the chunkwood system and leaves it with a small cost advantage. However, if a +1/8-inch flake classification is used, then the recovery from chunkwood improves so that the system has a cost advantage of about $24.05 per ton. Figures 7 and 8 illustrate material balances for +1/8-inch flake classifications. Should stumpage rates be increased to $15.00 per cord, as they are for some species in certain areas, then the +1/4-inch and +1/8-inch chunkwood systems would have $15.24 and $30.34 per ton advantages, respectively.

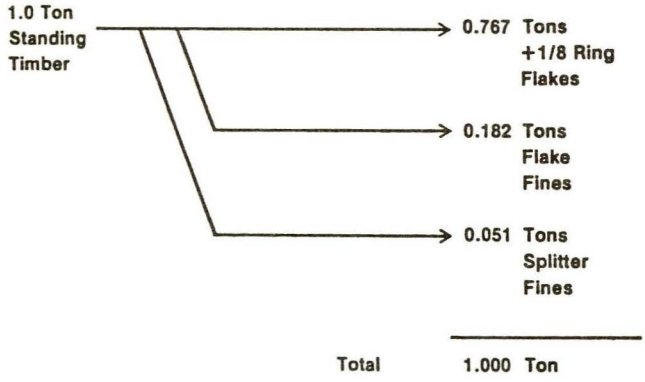


Figure 7.—*Material balance for producing ring flakes from chunks from 1 ton of standing timber O.D. (oven-dry) basis.*

The following calculations indicate the potential savings a 150-million square foot (1/2-inch basis) flakeboard plant could achieve by using the chunkwood system if it could utilize +1/8-inch flakes and had to pay $15.00 per cord for stumpage:

$$\$30.34 \times 150{,}000{,}000\ ft^2 \times \frac{.5\ in\text{-}ft}{12\ in} \times \frac{42\ lbs}{ft^3} \times \frac{1\ ton}{2{,}000\ lbs} = \$3{,}982{,}125 \text{ savings per year.}$$

Where specific cost elements are available, substitutions can be made to refine this estimate.

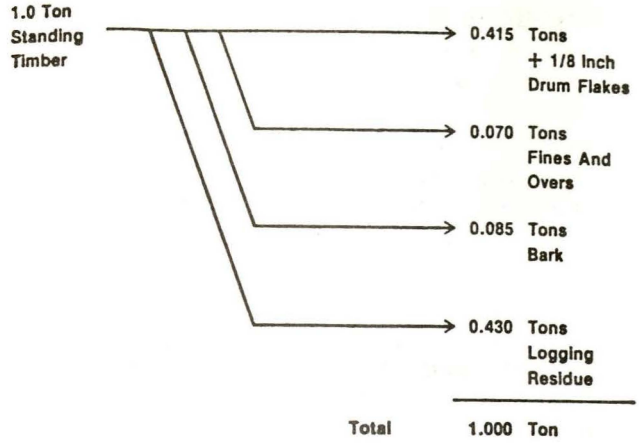


Figure 8.—*Material balance for producing drum flakes from roundwood from 1 ton of standing timber O.D. (oven-dry) basis.*

CONCLUSION

Chunked wood, as produced by the USDA Forest Service wood chunking machine, can be successfully used in the production of flakeboard. Mixtures of aspen flakes and red maple flakes made from chunked wood can be utilized to produce random and oriented strandboard and highly aligned panels with strength and physical properties that meet or exceed commercial standards.

REFERENCES

Arola, Rodger A.; Winsauer, Sharon A.; Radcliffe, Robert C.; Smith, Martyn R. 1983. **Chunkwood production: a new concept**. Forest Products Journal. 33(7/8): 43-51.

Bryan, Richard W. 1981. **Composite pine panel plant is the last word in versatility**. Forest Industries. 108(4): 34-37.

Dixon, Robert. 1981. **Elmendorf's 3-ply OSB receives APA rating**. Plywood and Panel. 24(6): 8-10.

Erickson, John R. 1976. **Exploratory trials with a spiral-head chipper to make hardwood "fingerling" chips for ring flakers**. Forest Products Journal. 26(6): 50-53.

Gardner, Rulon B.; Schaffer, Erwin L.; Erickson, John R. 1978. **Converting forest residue to structural flakeboard - the fingerling concept**. Res. Pap. INT-200. Ogden, UT: U.S.

Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 31 p.

Heebink, B.G. 1972. **Some views on large structural particleboard panels**. Res. Note FPL-0220. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

Heebink, Bruce G.; Dominick, Raymond F. 1971. **Forest residues: future source of particleboard**. Wood and Wood Products. 76(11): 26-28.

Heebink, Bruce G.; Schaffer, Erwin L.; Chern, Joseph; Haskell, James H. 1977. **Structural flakeboards using ring flakes from fingerling chips**. Res. Pap. FPL-296. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 11 p.

Hse, Chung-Yuu; Koch, Peter; McMillin, Charles W.; Price, Eddie W. 1975. **Laboratory-scale development of a structural exterior flakeboard from hardwoods growing on southern pine sites**. Forest Products Journal. 25(4): 42-50.

Northcross, Steve. 1982. **Potlatch commits Minnesota to OSB**. Plywood and Panel World. 23(10): 7-9.

Pease, David A. 1983. **Waferboard production unimpeded by rejects**. Forest Industries. 110(4): 32-34.

Price, Eddie W. 1977. **Basic properties of full-size structural flakeboards fabricated with flakes produced on a shaping lathe**. In: Maloney, Thomas, ed. Proceedings, 11th Washington State University symposium on particleboard; 1977 March; Pullman, WA. Pullman, WA: Washington State University: 313-332.

U.S. Department of Commerce. 1966. **Mat formed wood particleboard**. Commercial Standard CS 236-66. Washington, DC: U.S. Department of Commerce. 5 p.

Reducing Particle Dimensions of Chunkwood[1]

Robert C. Radcliffe[2]

Abstract.—Since the introduction of the chunkwood concept, several utilization opportunities have been proposed, ranging from its use as an intermediate furnish for flakeboard products to energy wood. Some uses, however, require wood particles smaller than typical chunks but larger than conventional pulp chips. Several methods are available to accomplish the size reduction of chunkwood. The chunker blade configuration has a profound effect on chunkwood particle size, with thicker blades producing proportionally smaller chunks. Four different blade geometries were investigated, including 1/4-inch-thick single- and double-bevel blades, 3/8-inch-thick single-bevel blades, and 1/4-inch-thick double-bevel blades with a 3/8-inch ramp attachment fixed to the cutting edge, effectively making them 5/8 inch thick. Fifty percent of the chunks produced by the ramp blades passed through a 2-inch screen, while only 20 percent of those produced by the 1/4-inch-thick blades did so. Three methods of particle size reduction totally separate from the chunking process were also investigated. One method involved an experimental machine that crushed logs prior to chunking, and two methods were postchunking approaches. A small, commercially available hammermill successfully reduced chunk size so that 85 percent of the particles passed through a 2-inch screen. The second method, an experimental spiked roll assembly, reduced the size of only the largest particles, allowing the smaller pieces to pass through relatively unprocessed. This device progressively reduced particle size by passage through the machine three times at decreasing roll spacings. Data are presented on the chunkwood particle size distributions before and after processing by each machine.

INTRODUCTION

In 1972 the USDA Forest Service began a 5-year effort to reduce residues on Forest Service lands. Under the umbrella of the Close Timber Utilization Project, researchers sought ways to utilize logging residues and small, low-quality trees recovered from thinnings. A potential target for the resulting fiber was the composite wood products industry.

Because of prior involvement with whole-tree chipping, research engineers at the Forestry Sciences Laboratory in Houghton, Michigan, were commissioned to develop a machine to produce wood particles from low-quality trees or logging residues. The wood particles were to have a greater length in the fiber direction than conventional pulp chips and be suitable for flaking. The prototype machine that resulted from this research produces chunky-shaped particles (chunkwood) (fig. 1) with an average fiber length of 2 to 4 inches that can have any cross section, including round pieces the full diameter of the tree or log.

---

[1]*Paper has been published as a North Central Forest Experiment Station Research Paper NC-296.*

[2]*Robert C. Radcliffe is Electronic Technician, USDA Forest Service, North Central Forest Experiment Station, Houghton, Michigan.*

Figure 1.—*Unreduced chunkwood.*

PROBLEM STATEMENT AND STUDY OBJECTIVE

If the technique of producing elongated flakes, which in turn are produced from chunkwood, is to gain commercial acceptance, practical methods must be developed to reduce the unacceptably large chunks into "fingerlings" of an acceptable size (Gardner *et al.* 1978). In an effort to determine if the individual particle size of chunkwood could be further reduced while maintaining fiber length, we conducted a series of experiments using different blade configurations on the prototype chunker, and on three methods of particle size reduction totally apart from the chunking process. The results are reported here.

CHUNKER DESCRIPTION

The mobile prototype wood chunker (Arola *et al.* 1988b, Barwise *et al.* 1984) (fig. 2) uses three curved, triangular cutting blades attached to a 36-inch carrier disc. The disc is driven by a 180-horsepower diesel engine through a speed reduction unit to obtain a disc speed of about 200 revolutions per minute (rpm). The disc allows for blade replacement and has facilities to mount blades of different thicknesses. The log is fed through a tubular anvil by hydraulically powered feed rollers that control the log feed rate. This machine is capable of processing tree-length material up to 9 inches in diameter. Because of the physical difficulties encountered when transporting and handling whole trees, only 8-foot logs were chunked to supply material for the following tests.

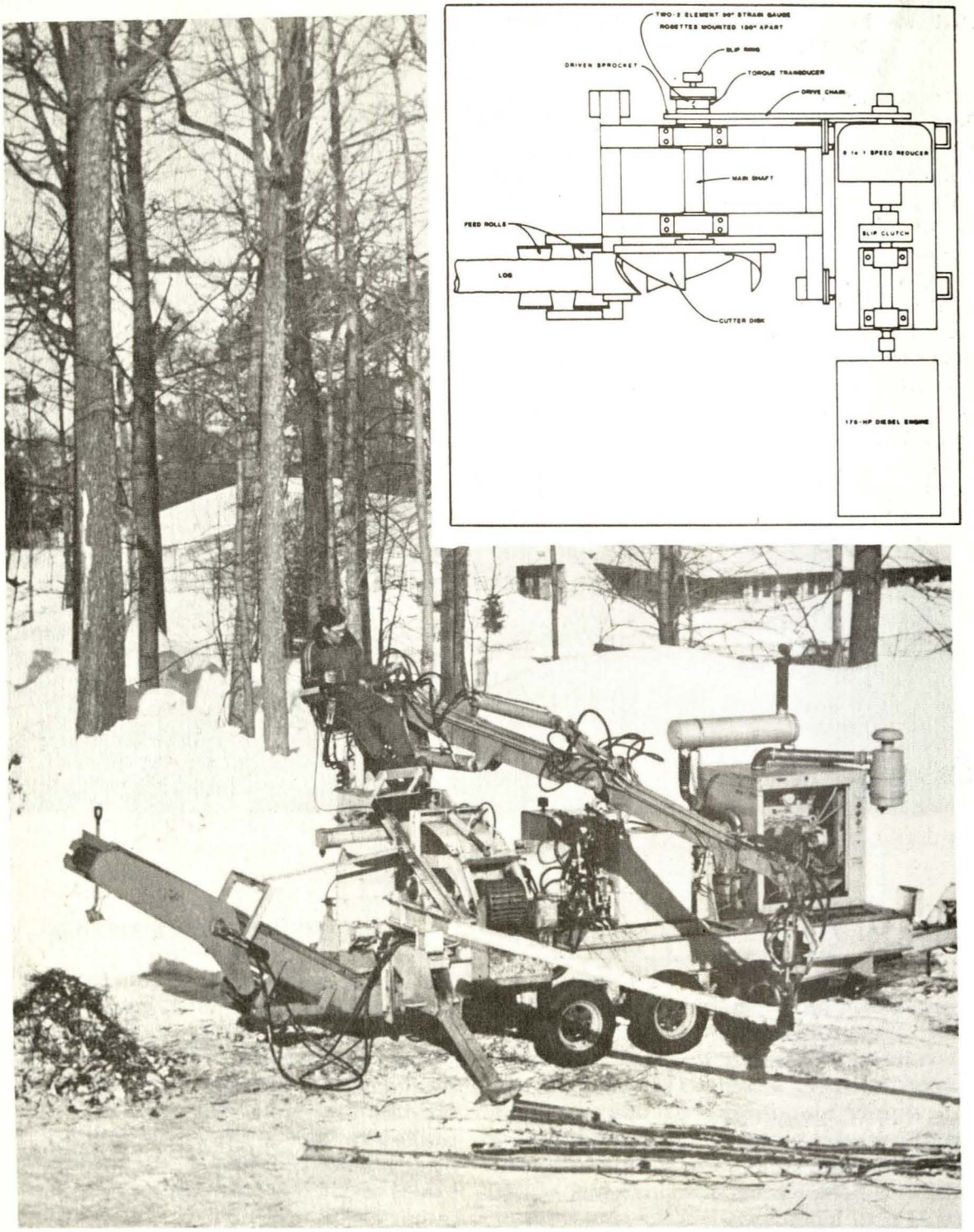
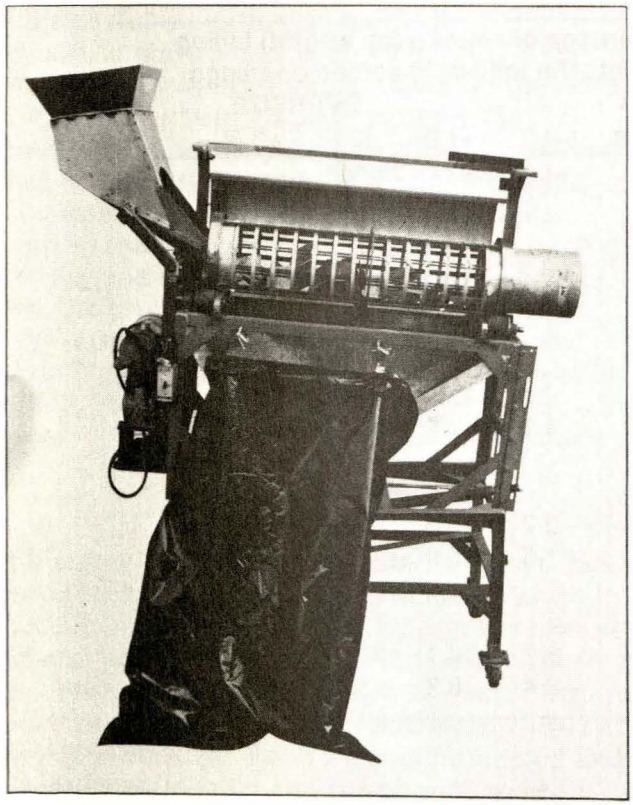


Figure 2.—*Photo and schematic of chunker.*

DETERMINATION OF PARTICLE SIZE AND METHODS OF ANALYSIS

A rotary square-hole screen classifier (Arola *et al.* 1988a) (fig. 3) was used to determine the particle size distributions of the chunkwood samples. The screens rotate about their longitudinal axes to impart a tumbling action on the chunks, facilitating discharge. The screens were used in descending order, the screen with the largest opening first. The particles that passed through the first screen were further classified by the screen with the next smaller opening. The classifier screen was inclined at an angle of 5 degrees from the horizontal, and the screen surface rotational speed was set at 78 feet per minute. The screens are composed of bars running the length of the screen. On all except the fines screen (0.2 inch), bands were placed around the circumference at distances corresponding to the bar spacing of the particular screen, to give an approximate square opening. The combination of slots and bands gave openings of 1.0, 2.0, and 2.5 inches. The 2.5-inch screen opening was later increased to 3.0 inches.



ANALYSIS TECHNIQUES

Although the chunks had a continuous distribution of sizes, the data consist of the percent by weight of chunks in discrete size fractions. The size categories depend on the screen selection and the size interval between screens. Therefore, nonlinear regression techniques were used to fit a continuous Weibull probability function of the form

$$E(Y) = 1 - \exp(-b_1 X^{b_2})$$

to the data to provide continuous curves for each treatment, reflecting the distribution of actual chunk weights. Because the primary focus of this research was the reduction of large particle, we defined a dependent variable "OVERSIZE" as the percent (by weight) of the particles that were retained on the screens with holes 2 inches and larger, for analysis of the difference among treatments.

CHUNKER BLADE CONFIGURATION TESTING

From prior work, we knew that blade thickness (1/4 vs. 3/8 inch) and cutting edge geometry (single vs. double bevel) have a significant effect on the resulting particle size (Arola *et al.* 1983). Because the 3/8-inch blades tend to break up the large discs more than the 1/4-inch blades, we theorized that a 3/8-inch-thick ramp attachment positioned at the cutter edge would augment particle breakup, producing even smaller particles. We tested each of the following blade configurations: 3/8-inch-thick single-bevel blades, 1/4-inch-thick single- and double-bevel blades, and 1/4-inch-thick double-bevel blades with a ramp attachment (fig. 4). The chunkwood produced by each blade set was quantitatively analyzed for particle comminution.

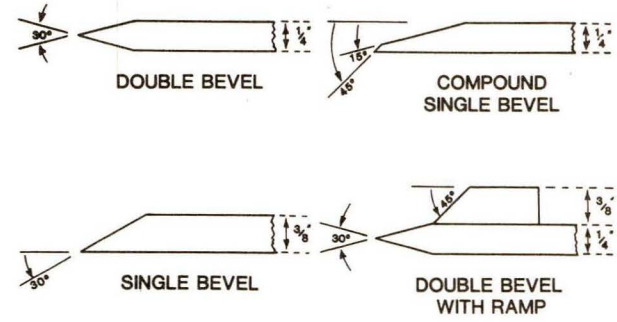


Figure 4.—*Schematic of chunker blades.*

Test Procedure

During the initial testing of the laboratory version of the chunker, log diameter appeared to influence chunk size. For that reason, the test logs were split into two size classes by average diameter: 2.8 to 4.7 inches for the small size category and 4.8 to 6.8 inches for the large. Forty 8-foot red maple (*Acer rubrum*) logs were numbered, measured for end diameters, and weighed. Ten logs were randomly selected, five in each size category for each blade set. The chunker blades were sharpened and installed prior to the testing sequence. The test logs were chunked, and the output was collected for subsequent classification, discarding the chunks that came from the ends of the log. After classification screening of the chunks (table 1), moisture content samples were taken from each screen fraction. Because moisture content was essentially constant across screen fraction sizes, an average moisture content is reported for each treatment.

Analysis

Analysis of variance (ANOVA) was used to determine if a difference in the percentage of large chunks (OVERSIZE) existed due to blade set or test log diameter (table 2). No statistically significant difference resulted from test log diameter, contrary to expectations based on previous chunking studies. This was probably due to the relatively small diameter range of the test logs. The interaction term between log diameter and blade set was not significant. The difference in the OVERSIZE category due to blade configuration was, however, significant at the 99-percent confidence level. Based on the ANOVA results, the diameter classes were combined for regression analysis to determine the Weibull cumulative distribution curves for the blade tests (fig. 5). R^2 values for the regressions were .97 or higher, indicating good fits. The actual regression coefficients obtained are presented in the appendix. Examination of the curves shows that the double-bevel ramp blade produced the most

Table 1.—*Effect of chunker blade configuration on chunk size distribution*

Blade type	Input weight	Moisture content	Percentage of chunks (by weight) failing to pass the following screen openings				
						OVERSIZE	
			Fines	+0.2[1]	+1.0[1]	+2.0[1]	+3.0[1]
	Pounds	*Percent*	*Inches*				
3/8" Single-bevel							
Mean	28.1	39	3.1	8.3	29.0	36.4	23.0
Std. dev.[2]	3.9		0.8	2.3	5.5	5.8	7.8
1/4" Single-bevel							
Mean	28.4	39	1.8	3.2	15.8	48.7	30.1
Std. dev.	2.8		0.6	1.7	4.6	13.5	15.4
1/4" Double-bevel							
Mean	27.5	37	2.2	3.7	23.8	37.0	32.8
Std. dev.	5.0		0.5	1.5	5.9	7.9	13.4
1/4" Double-bevel ramp[3]							
Mean	23.6	41	3.4	8.7	38.1	39.0	10.2
Std. dev.	5.1		1.0	2.4	5.2	5.2	5.9

[1] Size of screen opening.

[2] Standard deviation.

[3] Only four large logs were chunked with the 1/4-inch double-bevel ramp blades because of chunker malfunctions, resulting in nine observations for this treatment.

Table 2.—*Analysis of variance for blade configuration tests*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Blade set (B)	3	4,666.8	1,555.6	29.3
Log size (S)	1	18.2	18.2	0.3
Interaction				
B x S	3	285.8	95.3	0.2
Error	31	1,647.3	53.1	
Total	38	6,618.1		

[1] Dependent variable was OVERSIZE.

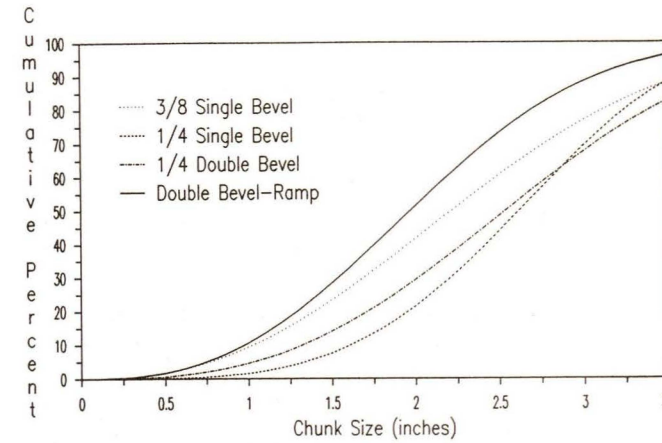


Figure 5.—*Weibull curves for blade data.*

small particles, with only 49 percent being in the OVERSIZE class. The 3/8-inch single-bevel blades left 59 percent of the chunks in the OVERSIZE category, whereas the 1/4-inch double- and single-bevel blade sets left 70 percent and 79 percent, respectively.

PARTICLE SIZE REDUCTION METHODS

We tested three mechanical methods of chunkwood particle size reduction. Two of the methods broke up the chunks, whereas the third crushed the log prior to processing by the chunker. The postchunking methods included a small, commercially available hammermill and an experimental device called the spiked roll assembly that broke down the chunks by forcing a pointed rod through the wood pieces. The third, the prechunking approach, was an experimental crusher (roll crusher) developed by the Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, Quebec (Barnett *et al.* 1986).

Sample Preparation

Each reduction method was tested on green logs of two species: red maple (*Acer rubrum*) and aspen (*Populus tremuloides*). All logs were 8 feet long and less than 8 inches in diameter. The logs were chunked using the USDA Forest Service chunker equipped with the 3/8-inch-thick single-bevel blades. Each log was numbered and chunked individually, and the chunks were collected and bagged separately.

For all test procedures, samples of the material were collected from each size fraction during screening for moisture content determinations made according to TAPPI Standard T 18m-53 (Technical Association of the Pulp and Paper Industry 1967). Moisture content is reported on a green-weight basis. Chunks and reduced material were screened by size with the rotary square-hole screen classifier and were analyzed using the same technique that was applied to the blade testing.

Hammermill

The Holmes model ADX[3] is a small hammermill (fig. 6) powered by a 3-horsepower, three-phase electric motor with a synchronous speed of 1,750 rpm. The material to be reduced is fed into a chamber enclosing three pivoted, weighted bars mounted on a rotating shaft. As the shaft rotates, the weighted bars impact the material entering the chamber, fracturing the larger pieces. To prevent overreduction of the chunkwood, the bottom retaining grate was removed, limiting particle residence time and facilitating particle discharge.

---

[3]*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. It does not constitute an official endorsement or approval of any product or service by the United States Department of Agriculture to the exclusion of others that may be suitable.*

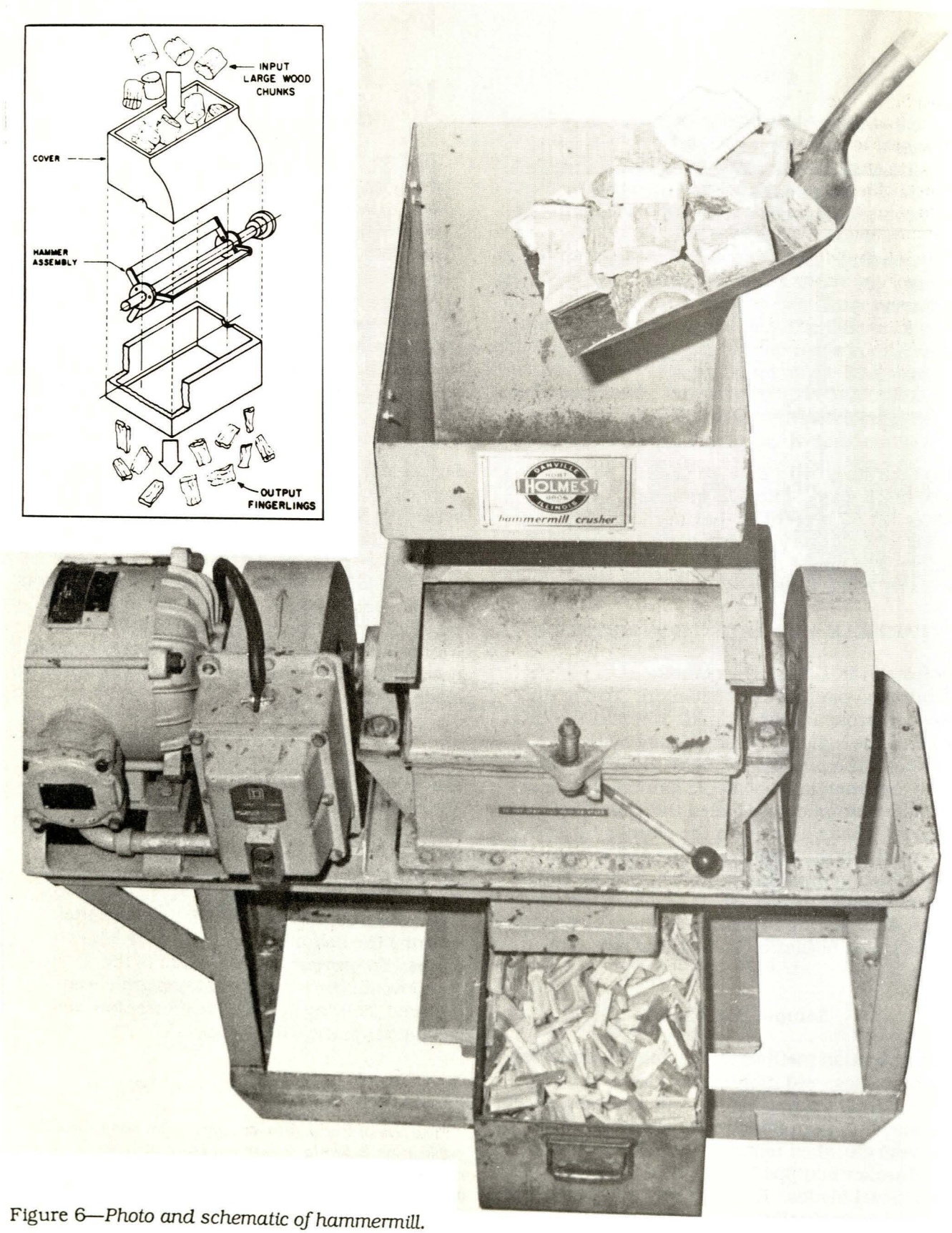


Figure 6—*Photo and schematic of hammermill.*

Test Procedure

Five randomly selected logs of each species were chunked individually, and the resulting output was divided into two samples: 25 percent for a control and 75 percent for processing by the hammermill. After the control sample was removed, the remaining chunks were weighed and dumped into the feed hopper of the hammermill. After one pass through the mill, the reduced particles were collected and reweighed to determine losses. Both the control and the hammermilled samples were screened for particle size distribution.

Analysis

Two-way analysis of variance (table 3), using OVERSIZE as the dependent variable, indicated a significant difference due to treatment (F = 156 with 1 and 16 d.f.). The ANOVA also indicated a significant difference due to species at the 95-percent level. The data show that more small particles were produced when chunking or hammermilling red maple than aspen, but the difference was not great enough to be of concern from a practical standpoint (table 4, fig. 7). Therefore, the two species were combined for the rest of the analysis.

Table 3.—*Analysis of variance for hammermill tests*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatment (T)	1	13,772.8	13,772.8	156.4
Species (S)	1	459.5	459.5	5.2
Interaction T x S	1	52.6	52.6	0.6
Error	16	1,408.6	88.4	
Total	19	15,693.5		

[1] Dependent variable was OVERSIZE.

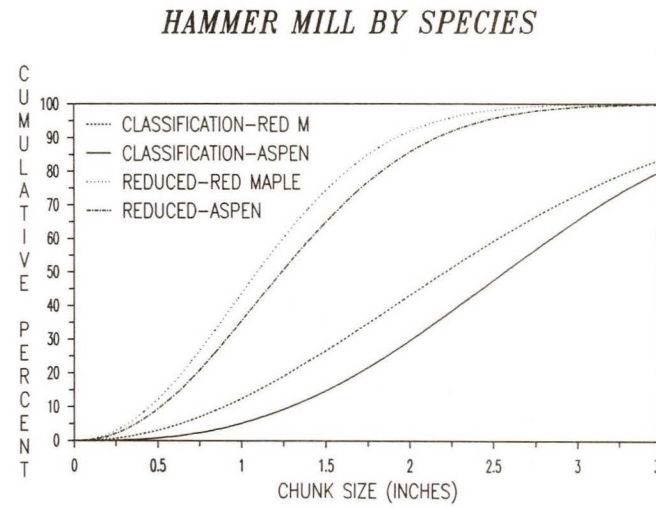


Figure 7.—*Weibull curves for hammermill data.*

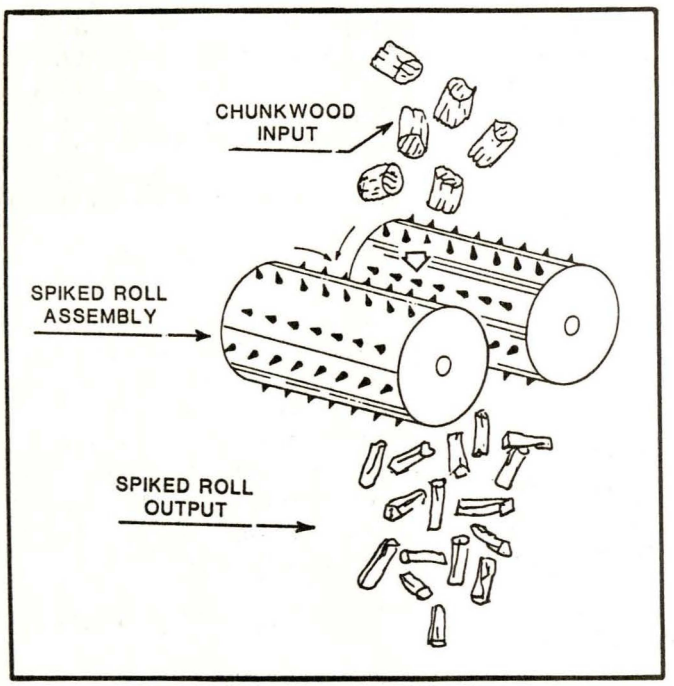
Table 4.—*Effect of hammermilling on particle size distribution*

	Input weight	Moisture content	Percentage of chunks (by weight) failing to pass the following screen openings OVERSIZE				
			Fines	+0.2[1]	+1.0[1]	+2.0[1]	+2.5[1]
	Pounds	*Percent*	- - - - - - - - *Inches* - - - - - - -				
Untreated							
Mean	24.8	39	4.6	8.9	22.4	15.4	48.0
Std. dev.[2]	0.3		2.6	4.7	7.2	3.0	15.2
Treated							
Mean	74.5	39	11.1	28.5	49.1	8.3	2.6
Std. dev.	0.3		1.6	4.0	2.9	2.6	1.5

[1] Size of screen opening.
[2] Standard deviation.

Experimental Spiked Roll Assembly

The spiked roll concept was initially developed by researchers at Michigan Technological University's Institute of Wood Research (Haataja *et al.* [1984]). The machine was designed by Michigan Tech mechanical engineering students under the guidance of a Forest Service engineer. The spiked roll assembly's principal feature is two opposing rolls with attached 6-inch-long spikes (fig. 8). The spikes were made from hardened 3/4-inch hex-head bolts with the threaded end sharpened to a 45-degree cone. The bolts were welded to the rolls on a 2- by 3-inch grid and placed so that the spikes of the opposing roll would intermesh. At the widest roll spacing, the



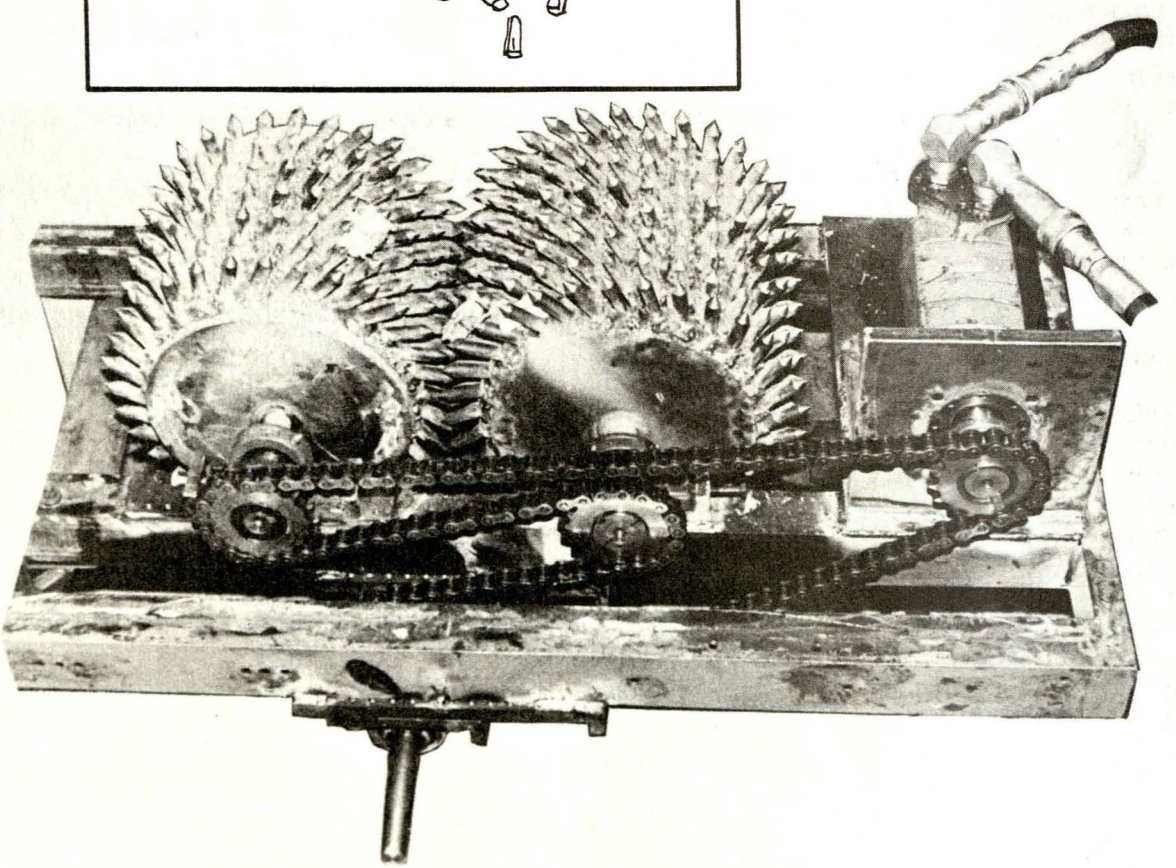


Figure 8.—*Photo and schematic of spiked roll assembly.*

spikes do not actually intermesh; the tips of the spikes of one roll are about 1 inch from the tips of the spikes of the opposing roll. The roll spacing, and hence the degree of intermeshing, was adjustable in 1-inch increments. The adjustments allowed settings of 1-inch separation between the tips of the rods, tips of the rods even with each other, and a 1- or 2-inch intermesh. The spikes are slightly inclined in the direction of rotation, providing easier spike penetration and a more aggressive feed. A 50-horsepower hydraulic power unit supplied power to a hydraulic motor, which in turn drove the rolls through a sprocket/chain assembly. An industrial version of this machine is envisioned as having multiple opposing roll pairs, adjusted so that the chunks would be progressively reduced to smaller particles as they pass through succeeding stages.

Test Procedure

To simulate the commercial version, all chunkwood samples were processed through the spiked roll assembly three separate times at decreasing roll spacings. As in the hammermill tests, five logs of each species were randomly selected and chunked, and 25 percent of the sample removed for the control. The remaining 75 percent was weighed and fed through the spiked roll assembly. The test sample was initially processed at the widest roll spacing of 1-inch tip separation and reclassified. The resulting material was then processed using a setting in which the spikes were even and finally processed at the closest spacing, which was a 2-inch intermesh. This procedure was followed for each test log.

Analysis

Analysis of variance was run on the spiked roll assembly data to determine if there was a difference in the percent of large chunks (OVERSIZE) due to treatment (each pass was considered a separate treatment) or species. Although a species difference was indicated, only the treatment differences were of consequence from a practical standpoint, so the species were combined for additional analysis (table 5). Post hoc T-tests on the mean values showed that, after each stage of treatment, the output from the spiked roll assembly contained a significantly (99-percent level) smaller percent in OVERSIZE. The percent of chunks (by weight) in OVERSIZE for untreated, stage 1, stage 2, and stage 3 were 72, 62, 40, and 7 percent, respectively, while the fines segment increased from 3.4 percent of input to just 6.9 percent of input. The output also became more homogeneous as chunks passed through the three consecutive stages, as the curves of the Weibull probability function clearly indicate (fig. 9, table 6).

Table 5.—*Analysis of variance for spiked roll assembly tests*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatment (T)[2]	3	24,316.9	8,105.6	264.2
Species (S)	1	561.8	561.8	18.3
Interaction T x S	3	78.4	26.1	0.8
Error	32	981.8	30.7	
Total	39	25,938.9		

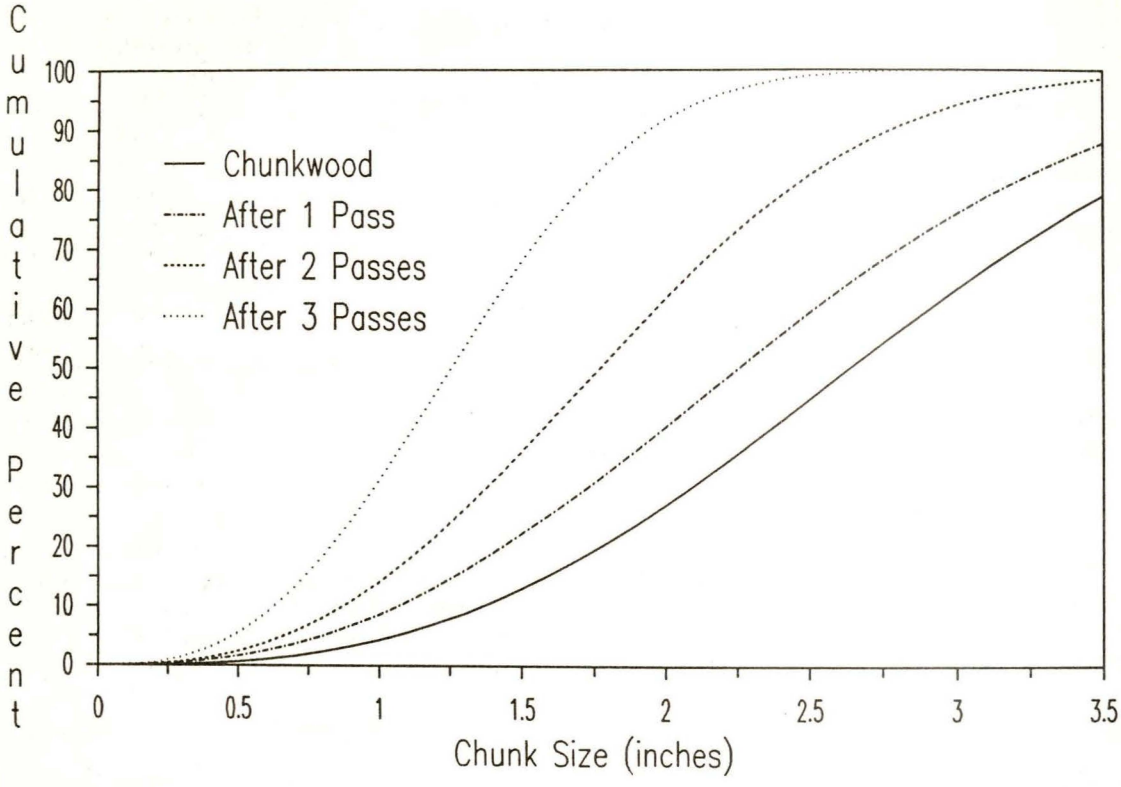
[1] Dependent variable was OVERSIZE.
[2] Four treatments—untreated, stage 1, stage 2, stage 3.

Experimental Roll Crusher

Researchers with the Forest Engineering Research Institute of Canada (FERIC) have developed a machine (fig. 10) to crush logs. We thought that chunking crushed logs might produce material that fits the description of "fingerlings" (Gardner *et al.* 1978).

The machine features two sets of opposing 18-inch-diameter crushing rollers fitted with ridged sleeves to prevent roll slip. Hydraulic cylinders exert a maximum downward force of 12,570 pounds upon each of the upper rollers. The motors for the rollers and the cylinders are hydraulically powered by a pump driven by a 427-cubic-inch displacement gasoline engine. The log (or tree) is placed between the first set of rollers and drawn in so that it is initially crushed by the first set of rollers. The partially crushed log is then drawn into the second roll set for the final crush. The severity of crushing of the first and second roll pairs is hydraulically adjustable.

Spiked Roll Assembly



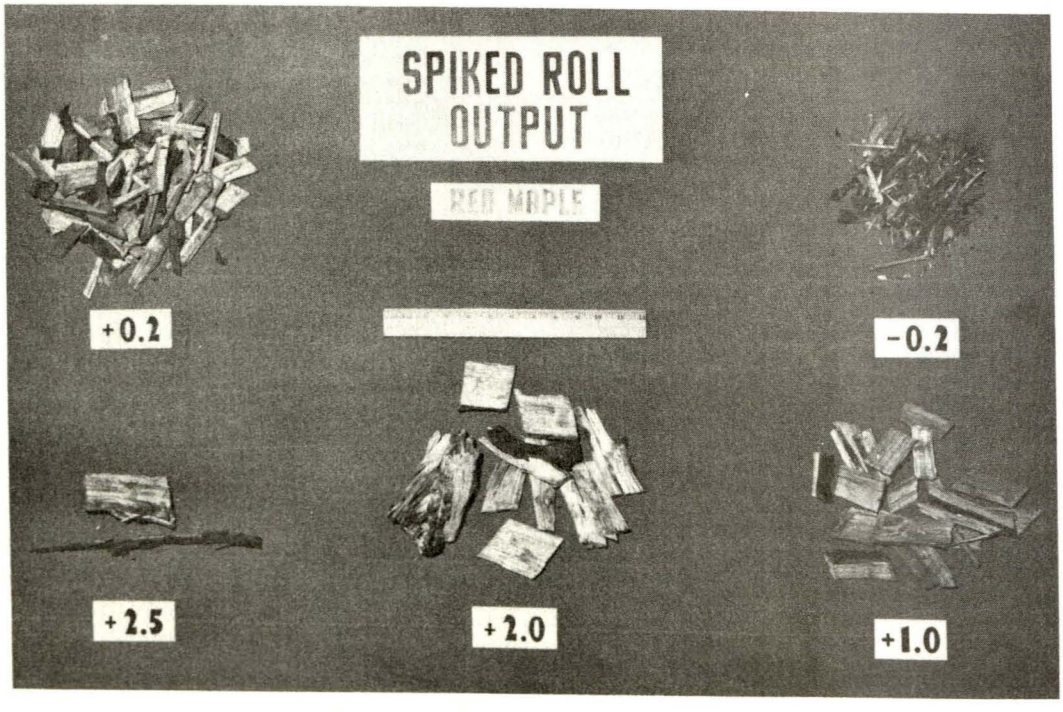


Figure 9.—*Weibull curves for spiked roll assembly.*

Table 6.—*Effect of the spiked roll assembly on particle size distribution*

	Input weight	Moisture content	Percentage of chunks (by weight) failing to pass the following screen openings				
						OVERSIZE	
			Fines	+0.2[1]	+1.0[1]	+2.0[1]	+2.5[1]
	Pounds	*Percent*	*Inches*				
Input							
Mean	24.7	39	3.4	6.8	17.8	14.4	57.2
Std. dev.[2]	0.3		2.2	3.3	4.6	3.3	11.7
Stage analysis							
Stage one (1-inch tip separation)							
Mean	74.7	39	4.0	8.2	25.4	23.3	39.0
Std. dev.	0.5		1.2	2.9	3.7	4.1	8.1
Stage two (1-inch spike intermesh)							
Mean	74.5	37	4.9	11.1	43.0	26.2	14.7
Std. dev.	0.5		1.3	2.7	2.8	2.9	4.2
Stage three (2-inch spike intermesh)							
Mean	74.3	39	6.9	24.0	60.9	6.5	0.9
Std. dev.	0.5		1.2	3.2	3.1	1.6	0.5

[1] Size of screen opening.
[2] Standard deviation.

Test Procedure

The control samples for the roll crusher tests were obtained by chunking similar logs of the same species and obtaining representative chunks. Ten logs of each species were then crushed and hand fed to the chunker in random sequence. From each crushed log, samples of about 25 pounds of chunks were collected and classified using the rotary square-hole screen classifier; they were analyzed as in the previous test procedures.

Analysis

Two-way ANOVA of the chunks from the roll-crushed material indicated a significant difference between treated and untreated logs at the 99-percent confidence level. No significant difference was found between species (table 7). The chunks in the control samples from the roll crusher tests were larger than those in the other control samples (hammermill, spiked roll, and 3/8-inch blade tests) (fig. 11). For unknown reasons, the control samples for the roll crusher averaged 90 percent OVERSIZE (standard deviation = 4.2), whereas the control samples from the other machines had an average of only 65 percent with a standard deviation of 11.7. Some possible causes are a change in cutter disc speed, a difference in wood condition (age, moisture, partially frozen, etc.), or a difference in chunker operation (table 8).

Table 7.—*Analysis of variance before and after roll crushing*[1]

Source	Degrees of freedom	Sum of squares	Mean square	F
Treatment (T)	1	25,996.5	25,996.5	284.1
Species (S)	1	23.0	23.6	0.3
Interaction T x S	1	0.8	0.8	0.01
Error	27	2,470.7	91.5	
Total	30	28,491.0		

[1] Dependent variable was OVERSIZE.

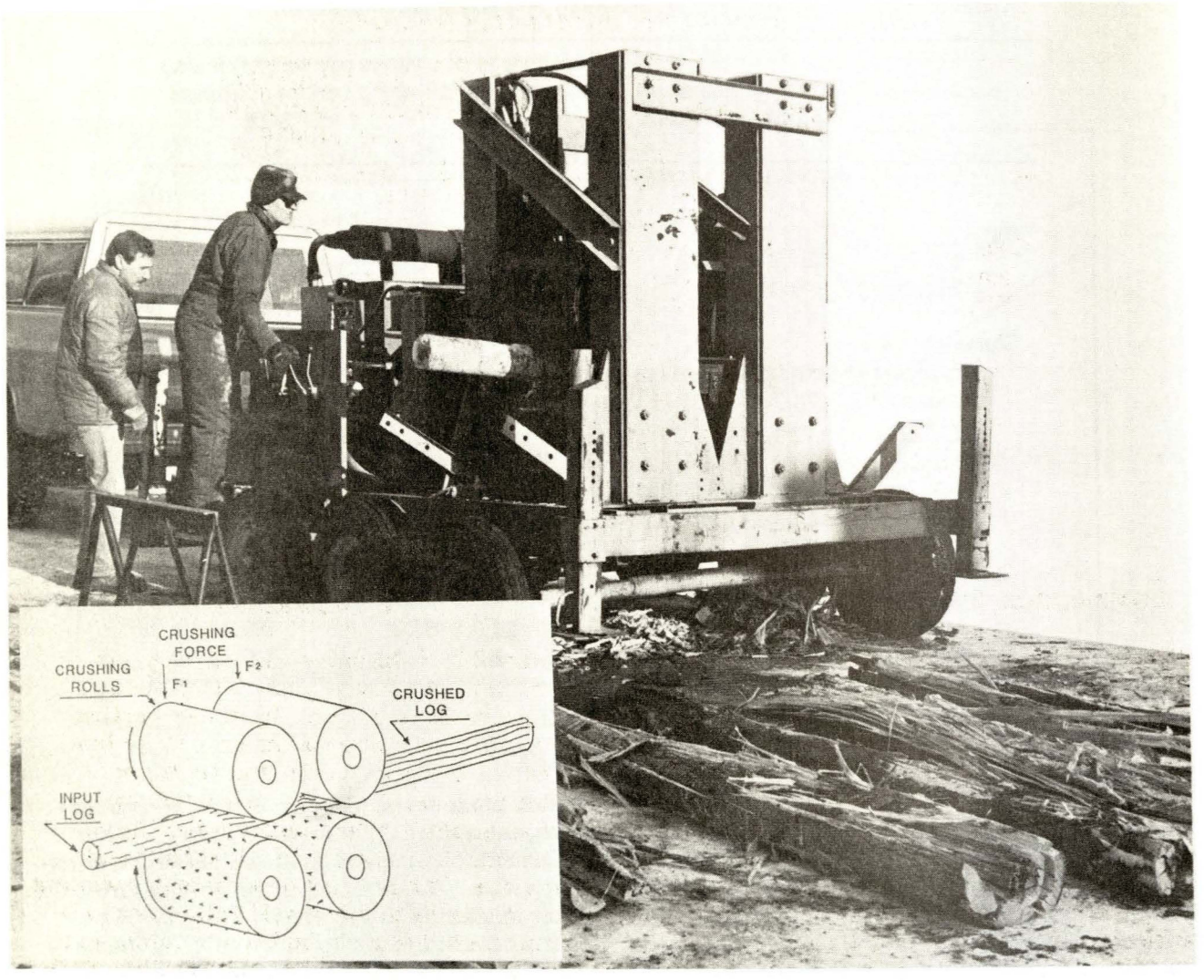


Figure 10.—*Photo and schematic of roll crusher.*

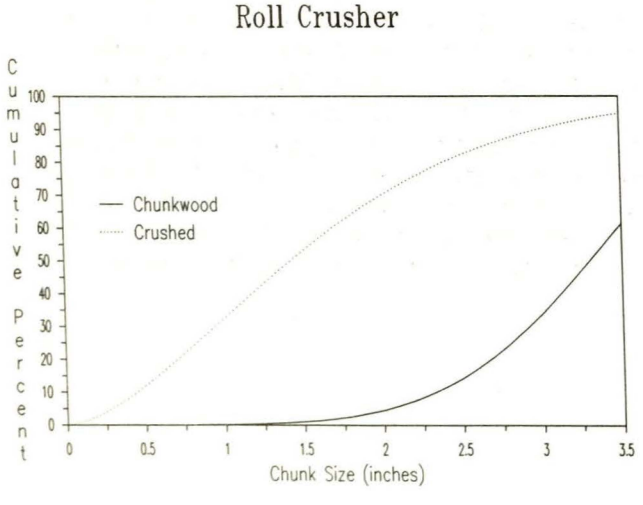


Figure 11.—*Weibull curves for roll crusher data.*

Table 8.—*Effects of chunking crushed logs on particle size distribution*

	Input weight	Moisture content	Percentage of chunks (by weight) failing to pass the following screen openings				
						OVERSIZE	
			Fines	+0.2[1]	+1.0[1]	+2.0[1]	+3.0[1]
	Pounds	*Percent*	*Inches*				
Chunks from uncrushed logs							
Mean	67.0	37	1.6	1.7	6.7	22.3	67.8
Std. dev.[2]	27.8		0.5	0.6	3.3	9.1	12.4
Chunks from crushed logs							
Mean	26.5	37	5.9	26.1	37.9	20.0	8.1
Std. dev.	3.5		2.2	6.3	4.8	4.9	8.4

[1] Size of screen opening.
[2] Standard deviation.

COMPARISON OF REDUCTION METHODS

All the reduction methods successfully broke down large chunks into smaller, more homogeneous particles (fig. 12). Three passes through the spiked roll assembly produced output very similar to the material that was hammermilled. About 80 percent of the material stayed on the 0.2- and 1-inch screens after these two treatments. The hammermill created more fines (11 percent) than the spiked roll assembly (7 percent) or the roll crusher (6 percent), due to the harsher treatment of the chunks (fig. 13). Although the roll-crushing treatment reduced the average particle size significantly, it was not as effective as the other two treatments nor were the resulting particles as homogeneous. Twenty-eight percent of the chunks (by weight) were still in the OVERSIZE category after chunking the crushed material, as opposed to about 10 percent after the hammermill or spiked roll treatments. This could be due, in part, to the same factors that produced larger chunks in the roll crusher control sample. In addition, the crushed logs did not chunk cleanly, and the resulting stringy pieces caused them to stay on the larger screens.

CONCLUSIONS

Chunker blade thickness has an impact on chunk size. A secondary factor is the cutting edge geometry; the double-bevel configuration produces smaller chunks than the single-bevel edge. The 1/4-inch single- and double-bevel blades produced 20 and 30 percent of the chunks under 2 inches, respectively. The 3/8-inch-thick blades produced 40 percent within that range. The 3/8-inch-thick ramp attachment to the 1/4-inch double-bevel blades (effectively making them 5/8 inch thick at the cutting edge) produced 50 percent of the chunks within the 2-inch target range.

The postchunking methods of reduction were effective in yielding a homogeneous output when compared with untreated chunks. Because the hammermill was a small unit, it could handle only 25 pounds in batch. The hammermill reduced the OVERSIZE segment of the output by about 83 percent. This type of hogging is presently used for fuel wood and could be applied on a commercial basis to size chunkwood. This process doubled the amount of fines, however, to 11 percent. The spiked roll assembly's through-

Figure 12.—*Comparison of chunkwood and reduced chunkwood.*

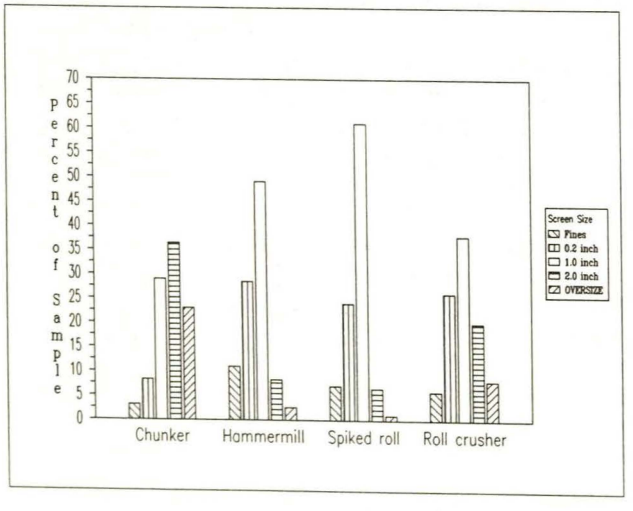


Figure 13.—*Comparison of chunkwood particle size distribution for reduction machinery.*

11 percent. The spiked roll assembly's throughput was much greater than that of the hammermill due to the continuous feed capability. It is envisioned that a commercial version of this machine would have successive stages, with each stage progressively reducing the larger particles. Our test machine had four possible settings, but in preliminary work we found that it performed well using only three. The setting where the opposing spike tips were even with each other did not appreciably improve particle reduction or machine performance so it was excluded from the test program. The reduced chunkwood output was quite homogeneous with a fines segment of only 7 percent. Because of the nature of this reducing method, the machine tends to reduce only the large pieces and does not increase fines content greatly. There were some problems breaking up the knotty pieces. The

knotty pieces, which were the major constituent of the OVERSIZE component of the output (7.4 percent of input), would jam between the spikes, especially on the closest setting. The hammermill, however, would simply discharge these pieces without reduction.

Although the roll crusher effectively crushed the logs, it was difficult to control the degree of crushing necessary for this study. When logs were run through this machine, they shattered so completely that they literally fell apart, which made feeding the chunker extremely difficult and chunker performance on the shattered logs less than ideal. When we attempted to restrict the degree of crushing so that the logs were well shattered but still retained some form, we had to continually adjust the rollers, making it impossible to maintain a constant crushing force, especially on smaller logs. The chunker blades would not cleanly sever the shattered logs, leaving long, splinter-like pieces in the chunker output. For this study, the roll crusher was a separate machine; the concept, however, could be incorporated into the chunker by replacing the feed rollers, which would possibly eliminate the log feed problem. A crushed log trapped between the rolls and positioned close to the chunker blades should restrain the wood enough for a clean cut. Although chunkwood reduction following roll crushing was not as complete as in the postchunking approaches, it resulted in a 72-percent reduction in the OVERSIZE category.

Chunkwood offers an alternative to typical wood chips. The chunky shape offers new utilization opportunities and cost benefits over current methods of wood comminution. Reducing the particle size while maintaining the chunky shape and the longer fiber length could provide the flakeboard industry and other wood users such as the pulp and paper industries with a tailored wood particle. Particles larger than pulp chips may prove superior for certain combustors. Finally, chunkwood from low-value poletimber stands, timberstand improvements, or logging residues could greatly extend the timber resource and perhaps provide a market incentive for thinnings and timberstand management.

LITERATURE CITED

Arola, Rodger A.; Radcliffe, Robert C.; Sturos, Joseph B. 1988a. **Characterizing chunkwood**. In: Production, storage and utilization of wood fuels: Proceedings of IEA/BE conference task 3/activity 6 and 7; 1988 December 6-7; Uppsala, SE. Res. Notes 133/1988. Garpenberg, SE: The Swedish University of Agricultural Sciences, Department of Operational Efficiency; 1: 49-67.

Arola, Rodger A.; Sturos, Joseph B.; Radcliffe, Robert C. 1988b. **U.S. chunkwood machines**. In: Production, storage and utilization of wood fuels: Proceedings of IEA/BE conference task 3/activity 6 and 7; 1988 December 6-7; Uppsala, SE. Res. Notes 133/1988. Garpenberg, SE: The Swedish University of Agricultural Sciences, Department of Operational Efficiency; 1: 1-20.

Arola, Rodger A.; Winsauer, Sharon A.; Radcliffe, Robert C.; Smith, Martyn R. 1983. **Chunkwood production: a new concept**. Forest Products Journal. 33(7/8): 43-51.

Barnett, Paul E.; Sirois, Donald L.; Ashmore, Colin. 1986. **Reduction of biomass moisture by crushing/splitting - a concept**. In: Rockwood, Donald L., ed. Proceedings of the 1985 southern forest biomass workshop; 1985 June 11-14; Gainesville, FL. Gainesville, FL: University of Florida, Institute of Food and Agricultural Sciences: 13-16.

Barwise, Robert D.; Arola, Rodger A.; Matson, Edsel D., inventors; the United States of America as represented by the Secretary of Agriculture, Washington, DC, assignee. 1984. **Involuted disc slicer**. U.S. patent 4,431,039. February 14. 11 p. Int. Cl.^{3} B27L 11/02. U.S. Cl. 144/176.

Gardner, Rulon B.; Schaffer, Erwin L.; Erickson, John R. 1978. **Converting forest residue to structural flakeboard—the fingerling concept**. Res. Pap. INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 31 p.

Haataja, Bruce A.; Adams, Roy D.; Arola, Rodger A. [1984]. **Total tree chunkwood as raw material for flake products**. In: Corcoran, Thomas J.; Gill, Douglas R., eds. COFE/IUFRO 1984: Proceedings of a symposium;

1984 August 11-18; Orono, ME; Fredericton, Canada. SAF Publ. 84-13. Orono, ME: University of Maine: 157-163.

Technical Association of the Pulp and Paper Industry. 1967. TAPPI Standard T 18m-53. **Specific gravity (density) and moisture content of pulpwood**. 4 p.

APPENDIX

Coefficients derived from nonlinear regression analysis for the Weibull probability function: $E(Y) = 1 - \exp(-b_1 X^{b_2})$ for the curves presented in the listed figures.

Blade tests—red maple only (fig. 5).

Blade type	n	b_1	b_2	r^2
3/8-inch single-bevel	50	0.0986	2.4505	0.98
1/4-inch single-bevel	50	.0164	3.8870	.97
1/4-inch double-bevel	50	.0470	2.8878	.97
1/4-inch double-bevel w/ramp attachment	45	.1125	2.6810	.99

Hammermill—individual species (fig. 7).

Treatment	n	b_1	b_2	r^2
Untreated aspen	25	0.0530	2.7293	0.93
Hammermilled aspen	25	.4381	2.1469	.98
Untreated red maple	25	.1334	2.0794	.94
Hammermilled red maple	25	.5740	2.1221	.97

Spiked roll by stages—aspen and red maple combined (fig. 9).

Treatment	n	b_1	b_2	r^2
Untreated	50	0.0438	2.8535	0.95
Stage 1	50	.0903	2.5157	.97
Stage 2	50	.1512	2.6699	.99
Stage 3	50	.3708	2.7462	.99

Roll crusher—aspen and red maple combined (fig. 11).

Treatment	n	b_1	b_2	r^2
Untreated	50	0.0011	5.3986	0.97
Crushed	105	.3898	1.6094	.96

Comparison of reduced chunks from three machines—aspen and red maple combined (fig. 13).

Treatment	n	b_1	b_2	r^2
Hammermill	50	0.5030	2.1106	0.97
Spiked roll	50	.3708	2.7462	.99
Crushed	105	.3898	1.6094	.96

☆U.S. GOVERNMENT PRINTING OFFICE: 1991-556-84340211

U.S. Department of Agriculture, Forest Service.
1991. **Chunkwood: production, characterization, and utilization**. Arola, Rodger A., comp. Gen. Tech. Rep. NC-145. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 104 p.

Presents a collection of U.S. research papers about chunkwood, an alternative form of comminuted wood particles that range from finger size up to fairly large, blocky particles of wood. Discusses chunkwood's characteristics, storage and drying, machinery, and use to build low-volume roads and as furnish for composite flake products.

KEY WORDS: Comminution, chunking machines, storage and drying, road building, fuel characteristics, flakeboard.

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.